

Principles and Problems of Environmental Pollution of Groundwater Resources with Case Examples from Developing Countries

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The principles and problems of environmental pollution and contamination are outlined. Emphasis is given to case examples from developing countries of Africa, Asia, and Latin America with a comparative analysis to developed countries. The problems of pollution/contamination are widespread in developed countries but are gradually spreading from the urban to rural areas in the developing countries. Great efforts in research and control programs to check pollution-loading into the environment have been made in the industrialized countries, but only negligible actions have been taken in developing countries. Pollutants emanate from both point and distributed sources and have adversely affected both surface water and groundwaters. The influences of the geologic and hydrologic cycles that exacerbate the incidences of pollution/contamination have not been well understood by environmental planners and managers. Professionals in the different areas of pollution control projects, particularly in developing countries, lack the integrated multiobjective approaches and techniques in problem solving. Such countries as Nigeria, Kenya, Brazil, and India are now menaced by pollution hazards. Appropriate methods of control are hereby suggested.

Introduction

Environmental pollution and contamination are becoming a common occurrence in parts of the developing world. It is difficult to distinguish precisely between pollution and contamination. In modern hydrogeologic literature, pollution is regarded as occurring in such high dosages or concentrations that it renders the polluted medium very hazardous or highly deleterious to biota. Contamination may occur to a lesser magnitude when compared to pollution, but it also may render the contaminated medium unusable or make it slightly hazardous to life. Many urban and rural areas of the developed or industrialized world have been adversely affected by large-scale pollution and contamination, resulting in losses of human, material and financial resources. In many American, European, and Asiatic countries, huge amounts of money are spent annually

for research to combat and control widespread pollutants and contaminants. Volumes of these pollutants/contaminants are produced yearly through natural and anthropogenic activities such as industrial activities, agricultural practices, waste disposal systems, etc. High-level, medium-level, and low-level wastes in solid, liquid, or gaseous forms are released into the environment at discrete intervals or on a continuous basis. These pollutants may be physical, chemical, biochemical, biological, or microbiological in nature. They may have short or long half-lives in the environment. They have continued to damage many environments of the industrialized countries, having defied many painstaking control programs (1,2). Many urban centers of developing countries are now also similarly threatened. Unfortunately, these poor countries lack the necessary expertise and funds to wage any meaningful war against pollution, which continues to spread unabated.

Parts of the environment currently being polluted include the atmosphere, pedosphere, hydrosphere, lithosphere, and biosphere. This paper shall focus on pollution/contamination of the hydrosphere, with particular emphasis on the groundwater regime, and pollution incidences in developing countries. The scope shall embrace sources and types of pollution/contamination, processes generating them, implications of geology/hydrogeology, and pollution dynamics and mechanisms. Potentials of groundwater pollution in developing coun-

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tries *vis-a-vis* the developed ones shall be outlined, highlighting their health hazards. Relevant suggestions for combating pollution more effectively shall be made. The primary objective is to review the general incidences of environmental pollution/contamination in relation to the effects of pedology and geology in close association with the dynamics of the hydrologic cycle. Proper understanding of sources and types of pollutants/contaminants and their genesis and hydrodynamics would help determine the appropriate control measures to be considered for the situation. The goal is to contribute to better control methods. It is believed that present control methods in parts of the world lack the depth of understanding required. In addition, many of these control efforts seem to be uncoordinated. Developing nations still at the threshold of widespread pollution/contamination could learn from the costly mistakes of the industrialized nations and hence take the necessary actions to protect their environments.

The natural processes and anthropogenic activities that generate pollutants/contaminants are many and varied, and so are their sources. The natural processes include products of soil and gully erosion, physicochemical weathering and mass wasting, sediment transport, floods, volcanic eruptions, seawater intrusions, etc. The manmade ones include industrial, agricultural, sewage wastes and lagoons, garbage dumps and barnyards, mining wastes, etc.

These pollutants/contaminants in one way or the other via the hydrologic cycle reach the groundwater systems to pollute/contaminate them. Through the circulation of water within the hydrologic cycle, pollutants on the ground surface are transferred through the soil zone into the aquifer horizons where they damage potable water supplies. To reduce degradation of these water supplies, a comprehensive management strategy is required, as discussed later. The present control techniques with regard to pollution and contamination hazards, particularly in developing countries, need to be greatly improved. Priority and concern are not shown adequately by government authorities, and hence, appropriate planning and management strategies to check pollution are generally absent. The expertise or requisite manpower may be lacking. Funds for basic research may not be provided. Environmental protection laws or edicts may be nonexistent and where available are rarely enforced. These have exacerbated the spreading phenomenon of many pollutants/contaminants in many developing countries. In this review, necessary suggestions for improvement of this situation shall be given.

Sources and Types of Pollutants/Contaminants

The two main sources of pollutants/contaminants are point sources (Table 1) and distributed sources (2) (Table 2). Pollutants/contaminants from the two sources may be released continuously (3) or at discrete intervals

Table 1. Point sources of pollution and contamination.

Type of pollution	Examples
Sewage disposal systems	Sewage lagoons Septic systems Cesspools Barnyards/feed lots
Surface waste disposal sites	Landfills/garbage dumps Surface waste dumps
Underground waste disposal sites	Storage tanks (low-, medium-, high-level wastes) Pit latrines, tunnels, trenches, caves
Spills, washings, and intrusions	Waste subsurface injections Oil/gas/waste spills Auto workshop washings Research/laboratory washings Seawater/saltwater intrusions
Mining sources	Acid mine drainages Gas explosions/seepages Mine dumps and gangue deposits Tunnels/excavations outflows
Natural mineral/ore deposits	Saline ponds/lakes Hot springs/mineralized waters Anhydrite/pyrite deposits/evaporites

Table 2. Distributed sources of pollution and contamination (1).

Source	Examples
Agriculture	Cropland Pasture and rangeland Irrigated land Wood land Feed lots
Silviculture	Growing stock Logging Road building
Construction	Urban development Highway construction
Mining	Surface Underground
Terrestrial (many and scattered)	Landfills Dumps
Utility maintenance	Highways and streets Deicing
Urban run-off	Floods and snowmelt
Precipitation	Rainfall, snowfall, etc.
Background sources	Native forests Prairie land, etc.

(4). Point sources of pollution can be geometrically defined and the dimensions amenable to mathematical analysis in assessing pollution loads and rates of discharge determined. Point sources of pollution may assume any geometrical shape such as circular, triangular, spherical, etc. The areal sources of pollutants/contaminants or leachates are comparatively smaller, easily mappable, and readily distinguishable. However, where the input/output load functions from point sources into the hydrogeologic environment are continuous, the polluted/contaminated area may eventually become widespread. Distributed sources of pollutants/contaminants are much more widespread and can rarely be geometrically defined as precisely as a point source. Hence, it is more difficult to subject the input/output source to

precise mathematical analysis. Rather, a measured and intelligent assumption of the affected area is made for use in modeling and analysis. In heavily polluted/contaminated areas, both point sources and distributed sources may be occurring together or may be independent of one another. Successful control methods or mathematical modeling of the affected/polluted area must recognize this situation in order for the control program to be effective.

Point Sources of Pollution/Contamination

In the list of point sources given in Table 1, the pollutants or contaminants come from zones or areas of known and definable boundaries that are easily amenable to mathematical analysis and modeling. The pollution loads can be controlled at the point of input before they can spread into the surrounding environment in a time-discrete or continuous manner. Point sources include sewage lagoons (solid, gaseous, and liquid), industrial wastes, landfills/garbage dumps/barnyards, liquid/gaseous spills (oil, chemicals, etc.), mining (pits, holes, excavations, wastes, and gangue minerals), saline lakes and deposits, evaporite sequences, etc. Through the complex interplay of various soil and geologic factors and rain/water events of the hydrologic cycle, pollutant/contaminant substances reach the groundwater systems to pollute them. For example, buried refuse or garbage undergoes biodegradational decay in the pedologic/soil zone. The resulting leachates are released into the groundwater flow system where dissolved geochemical constituents are transported in various distances and directions. Piled up animal wastes in barnyards or liquid wastes in lagoons are similarly leached out and transported causing pollution of surface waters and groundwater areas. In many developing countries today, industrial and domestic wastes are indiscriminately dumped into rivers, lakes, streams, dry valleys, etc. This was the case in many developed countries, and such practices still persist in some of them today. These wastes damage surface waters and eventually destroy parts of the groundwater regime. Mining wastes and gangue products and other point sources of pollutants/contaminants produce similar havoc for the environment (4-9).

Distributed Sources of Pollution/Contamination

Distributed sources of pollutants/contaminants given in Table 2 are those in which the pollutants or contaminants are spread through a large area of hydrogeologic environment and in which they extend over the entire source area. A distributed source is very widespread, and the pollutants/contaminants may be introduced from various sources and directions. Spreading is enhanced by wind, rain, and snowfall activities through atmospheric circulation and precipitation. The areal extent or boundary conditions for the pollutants are difficult to define because of the regional nature of sources,

thereby posing problems for mathematical analysis. The sources include acid-alkaline rain, floods, erosion, agricultural fertilizer applications, and generated agricultural wastes, seasprays and intrusions, volcanoes, etc. Acid rain is a major distributed source of pollution in developed countries such as the United States, Canada, Germany, etc. Localized pollution of groundwater by acid rain in some developing countries such as Nigeria has been reported (10). Surface waters and shallow groundwater are polluted by atmospheric fallouts (3,11-13). In urban, suburban, and rural areas of many developing countries, particularly in the tropics, soil and gully erosion produce heavy sediment loads carried by floods that pollute surface water and groundwater systems (14-19). Waste products in urban areas are transported away by runoff. In mining areas, gangue materials dumped about recklessly on ground surface, decay and liquid wastes are leached from them becoming components of the hydrogeologic environment (20-22). In regions of intense geomorphic degradation and mass-wasting, physicochemical and biological weathering disintegrate pedologic and geologic materials to produce sediments that provide great quantities and varieties of pollutants. Fallouts from volcanic activities or atmospheric tests in one area may be spread into other regions of the world; wind, wave action, seaspray, or saltwater intrusion may drive contaminants inland and road salt application for de-icing during winter and widespread fertilizer usage, particularly in developed countries, are also major distributed sources of pollution. Similar events are now becoming prevalent in developing countries, particularly the industrializing ones.

Biological Pollutant/Contaminants in Groundwaters

Biological pollutants of groundwaters include dissolved organic constituents and microorganisms that seep or leach into groundwaters from polluted surface waters. Microorganisms may contribute to pollution in many ways, namely they may themselves be pathogenic; aesthetically they may produce undesirable biomass, or they may generate toxic metabolites in the groundwater. The microorganisms may be either pathogenic or nonpathogenic. In both cases, they produce undesirable effects in the groundwater itself and in the distribution network (where water may be distributed for domestic uses) and the populations using it.

Pathogenic Microorganisms. Pathogenic microorganisms are present in groundwaters, especially in the vicinity of facilities that are discharging sewage effluents or contaminated surface waters, and new septic tanks, agricultural wastes, and refuse tips. Microorganisms, however, must survive the tortuous task of passing through the soil cover, which constitutes an excellent natural process for water filtration and treatment. Even with this barrier, it follows that the nearer these sources of pollution are to groundwater sources, the greater the chance of successful seepage of these

microorganisms. Shallow wells and some deep boreholes are prone to contamination by these pathogens.

The isolation of pathogenic microorganisms from groundwaters is difficult but, when achieved, it serves as obvious proof of potential danger to the users, regardless of the number of pathogens present. Generally, however, the majority of waterborne pathogenic microorganisms enter water supplies as a result of fecal contamination. Therefore, the ability to detect fecal contamination at low levels is the main safeguard in preserving the potability of water supplies (23). Pathogenic microorganisms normally associated with water supplies are shown in Table 3 (24). All of these have been isolated from contaminated shallow wells and deep boreholes in Kaduna, Kano, Niger, and Plateau States of Nigeria (25). In addition, *Dracunculus medinensis* (Guinea worm) was reported from wells in parts of Nigeria such as in Kwara State (25). These parasites are widespread in many parts of Nigeria, sometimes occurring in epidemic proportions.

Fecal contamination in water is usually demonstrated by the detection of specific bacteria that are present in very large numbers in the intestines. The test normally employed is the presumptive Coliform test, which involves the most probable number (MPN) counts using liquid media. Coliform organisms include *Escherichia coli*, *Citrobacter*, *Klebsiella*, and *Enterobacter* spp., which are members of the family Enterobacteriaceae. They are gram-negative, oxidase-negative, nonspore-forming rods that can grow aerobically in a medium containing bile salts. They are able to ferment lactose within 48 hr, producing acid and gas at 37°C. A presumptive coliform test with a very high count is usually

followed by a confirmatory test which is specific for *E. coli* (26).

Nonpathogenic Microorganisms. Many nonpathogenic bacteria are as important as the pathogenic ones in the pollution of surface water and groundwater supplies. These include the sulfur and iron bacteria. Among the sulfur bacteria are the sulfate reducers such as *Desulfovibrio*, *Desulfomonas*, and *Desulfotomaculum*, which produce elemental sulfur from sulfates. On the other hand, some of the sulfur bacteria oxidize elemental sulfur to sulfates, all of which involve complex oxidation-reduction reactions. These include the ubiquitous chemolithotrophic *Thiobacillus* and the filamentous gliding bacteria *Beggiatoa* and *Achromatium*. The sulfur-oxidizing bacteria normally associated with groundwaters have been described by Trudinger (27), LeGall and Postgate (28), and Ehrlich (29) (Table 4).

Iron bacteria are frequently present in groundwaters and in particular those subject to a degree of organic pollution. They obtain energy for their metabolism by the oxidation of ferrous and/or manganous ions. These include the gliding bacteria *Toxothrix*; the sheathed bacteria, *Spaethilus*, *Leptothrix*, *Crenothrix*, and *Clonothrix*; the budding and/or appendage bacteria, *Pedomicrobium*, *Gallionella*, *Metallogenium*, and *Kusnezovia* and the gram-negative chemolithotrophic bacteria, *Thiobacillus* (*T. ferrooxidans*), *Siderocapsa*, *Naumaniella*, *Ochrobium*, and *Siderococcus* (30). Pathogenic and nonpathogenic microorganisms (bacteria, fungi, viruses) are thus hazardous environmental pollutants to the hydrogeologic environment. They enter this environment from waste disposal and treatment areas, sewage lagoons, barnyards, landfills, and mine areas (31).

Table 3. Pathogens associated with water supplies.

Pathogens	Diseases caused
Bacterial	
<i>Salmonella typhi</i>	Typhoid fever
<i>Salmonella paratyphi</i> A and B	Paratyphoid fever
<i>Salmonella typhimurium</i>	Salmonellosis
<i>Shigella sonnei</i>	
<i>Shigella dysenteriae</i>	Bacillary dysentery
<i>Shigella flexneri</i>	
<i>Mycobacterium tuberculosis</i>	Tuberculosis
<i>Vibrio cholerae</i>	Cholera
<i>Francisella tularensis</i>	Tularaemia
Enteropathogenic <i>Escherichia coli</i>	Enteritis
<i>Leptospira icterohaemorrhagiae</i>	Leptospirosis
Viral	
Hepatitis A virus	Viral hepatitis Type A
Enteroviruses (polio, Coxsackie A and B and echo)	Respiratory tract infection, nonbacterial enteritis
Adenoviruses	
Parvoviruses	
Reoviruses	
Protozoan and metazoan	
<i>Entamoeba histolytica</i>	Amoebic dysentery
<i>Acanthamoeba</i> spp.	Amoebic meningoencephalitis
<i>Naegleria</i> spp.	Amoebic meningoencephalitis
<i>Giardia lamblia</i>	Giardiasis
<i>Ascaris lumbricoides</i>	Helminthiasis
<i>Trichuris trichura</i>	
<i>Taenia</i> spp.	

Table 4. Sulfur oxidizing bacteria in groundwaters.

Genus or group	Habitat
Chemotrophs	
Sulfobacillus	Mine tips
Thiobacillus	Water, soil, marine
Sulfolobus	Geothermal springs
Thiobacterium	Water
Macromonas	Water
Thiovulum	Water
Thiospira	Water
Beggiatoa	Water, soil, marine
Thioploca	Water, soil
Thiothrix	Water, soil, marine
Achromatium	Water
Thiodendron	Water, soil
Phototrophs	
Chromatiaceae (purple S bacteria)	Water, marine
Chlorobiaceae (green S bacteria)	Water, marine
Chloroflexaceae	Geothermal springs
Oscillatoria (Blue-green algae)	Water

They occur in varying degrees in both oxidizing and reducing environments. In the process of complex redox activities that break down organic and inorganic materials to release energy for metabolic activities, poisonous substances are generated that may be fatal to the hosts that ingest them. These redox microbial activities may also degrade their habitats, rendering them unusable. Such degraded states may remain so for a long time.

Organic Pollutants in Groundwater

Organic pollutants that may be found in groundwater through shallow wells and deep boreholes include dissolved organic carbon (DOC) and particulate organic carbon (POC). They, in association with microorganisms, cause destructive pollution or contamination in hydrogeologic environments. They may serve as nutrient/energy sources for microorganisms. Where they are heavily loaded into groundwaters, DOC and POC enhance microbial multiplication and growth, thereby rendering the habitat anoxic. In such environments, denitrification, desulfurization, etc., are rampant, engendering an abundant growth of bacteria, fungi, and viruses that may be highly pathogenic. Hence, serious organic pollution signals a potential heavy microbial pollution of a groundwater system.

Thermal Pollution/Contamination

Thermal pollution/contamination may result from two main sources, namely, industrial and geothermal pollution. In industrialized countries and some developing ones, heat generated by industries is discharged through wastewater into the environment. High temperature waters eventually reach shallow aquifers and adversely affect groundwater. Hot waters discharged into lakes that are influent may form high temperature haloes that extend into the aquifers underlying the lake. Unchecked thermal pollution not only negatively affects

the life in the lake but also that of the groundwater system associated with the lake. Other problems that can arise are the changing of physical, chemical, and biological characteristics of the hydrogeologic system, thereby rendering the surface water and groundwater unusable.

In many parts of the world, the locations of geothermal pollution hazards are known. Geothermal pollution is much more common in tectonically unstable environments where high temperature effluents and gases emanate from deep horizons or the core within the earth. They move up to the shallow hydrogeologic zones through fractures (joints, faults, shear zones) and heat up surrounding groundwaters to generate hot and warm springs. In addition to the hotness of such waters, they are also highly mineralized because the high temperatures enhance the dissolution of soil and geologic materials.

Geologic and Hydrologic Cycles

Pedologic, geologic, and hydrologic cycles have several components and characteristics that enhance or aggravate the incidences of pollutant/contaminant origin, transport, and spread through hydrodynamic dispersion (diffusion, advection and dispersion) into the hydrogeologic environments that embrace the atmosphere, pedosphere, lithosphere, hydrosphere, and biosphere.

Geologic Cycle

Geologic rock units may be fractured, faulted, and jointed during tectonic movements or may be layered during the deposition and consolidation of sediments. Weathering disaggregates rocks into soils and sediments that are transported away by wind, water, and/or man. During these processes of the geologic cycle, pollutants and contaminants may be formed or released. Figure 1 shows significant parts of the complex geologic cycle that are relevant to groundwater pollution. Soil and geologic characteristics vary in horizontal, lateral, and vertical directions. Soil characteristics include grain size, porosity, permeability, stress-strength properties, cohesiveness, and other physical and chemical properties. The soil components of unconsolidated geologic units that form aquifers have similar physicochemical characteristics. Additionally, layering or stratification properties of both consolidated and unconsolidated geologic units are factors that affect pollutant/contaminant inputs, transport and dispersion. Stratigraphic properties of directional lithologic changes, facies changes, stratification and stratal thicknesses, degrees of sedimentation, cementation, and diagenetic changes affect the life of pollutants/contaminants in groundwater (Fig. 2) (14). The structural characteristics of fractures, faults, joints, and folds (Fig. 3) of igneous and metamorphic rocks and consolidated sedimentary rocks are also significant in groundwater pollution and contamination.

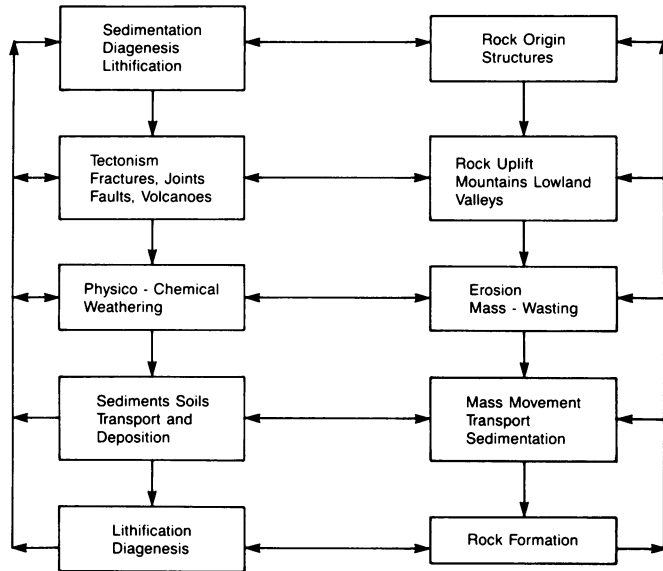


FIGURE 1. Geologic cycle.

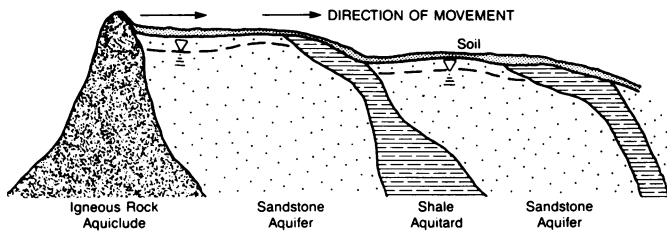
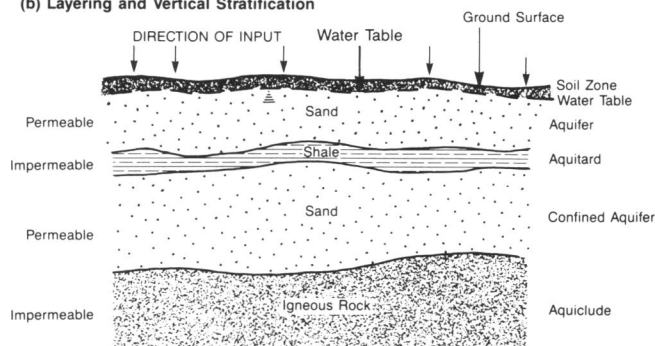
(a) Horizontal Stratification and Facies Changes**(b) Layering and Vertical Stratification**

FIGURE 2. Lithologic changes.

Subsequent discussions of the geologic and hydrogeologic settings shall explain further the obvious implications of these properties in the genesis, transport, and dispersion of pollutants/contaminants in groundwater flow systems. It will then be clear that any successful stoppage or control of groundwater pollutants and contaminants must take into serious consideration the implications of geologic and hydrogeologic characteristics of the particular polluted or threatened environment. Currently, pollution/contamination planners and managers do not seriously consider geologic prop-

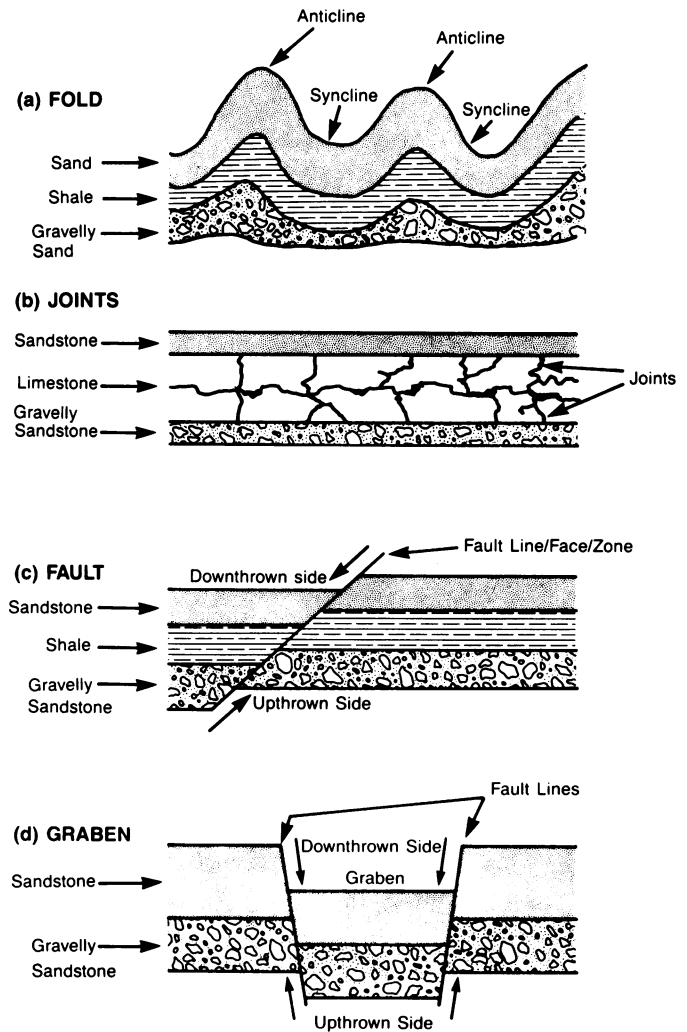


FIGURE 3. (a) Folds, (b) joints, (c) fault, (d) graben.

erties and characteristics in design and control programs, thereby creating situations that frequently produce failures in engineered structures.

Hydrologic Cycle

The several processes as briefly outlined below that occur within the hydrologic cycle (Fig. 4) are the driving forces and agents of groundwater pollution. The atmosphere serves as the gaseous envelope surrounding the earth. Precipitation through condensation of rain clouds falls down to earth as rain, snow, hail, etc. Atmospheric pollutants and contaminants may be washed out of the atmosphere as fallout. Runoff carries pollutants into surface waters for possible evaporation back into the atmosphere or storage in rivers, streams, lakes, and oceans, seas, etc. Some of the fallout or rainout may infiltrate into the soil zone to be evapotranspired to the atmosphere or percolate into the groundwater zone. Here moisture joins a complex hydrodynamic flow sys-

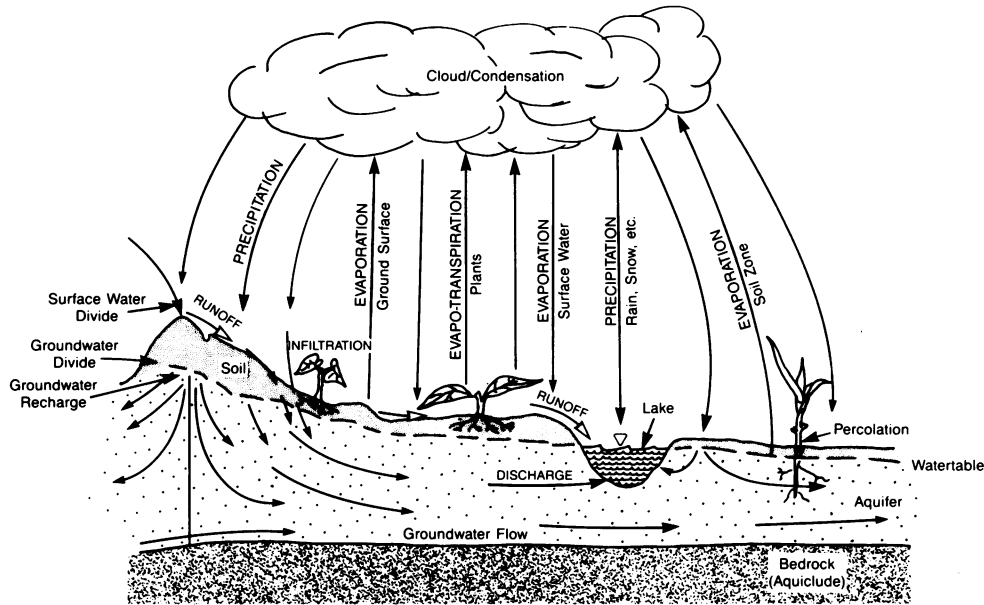


FIGURE 4. The hydrologic cycle.

tem possibly to be transported to the oceans or other surface waters where evaporation may return the water back to the atmosphere. In all these processes, pollutants and contaminants may be produced and cyclically dispersed from one point of the hydrologic cycle to another. This is graphically shown in the cyclic pollution/contamination of the hydrogeologic system otherwise called the hydrogeopollution cycle (Fig. 5). Pollutants and contaminants may be generated through natural or anthropogenic processes and circulated in the environment (atmosphere, pedosphere, lithosphere, biosphere,

and hydrosphere) through the activities of air, water, chemical, physical, and microbiological processes. These complex and cyclic processes may be continuous with respect to distance and time and may be localized or regional in areal spread. Thus, pollution at one source or an area may threaten nearby or distant places unless its spread is checked or controlled.

The implications of the geologic and hydrologic cycles are much more pronounced when one relates them to the long half-lives and transport of high-level radioactive wastes from industries. These materials are being stockpiled in different parts of the industrialized nations and some developing countries waiting to be safely disposed of in secure geologic rock units. It is now known that even deep-seated geologic hard rock formations have cracks, joints, and even faults through which moving groundwaters can transport pollutants/contaminants in many directions. It is also possible that the grain size and lattice structure of such rock units may permit widescale diffusion/dispersion of gaseous/liquid pollutants that may eventually threaten the biospheric environment with time. Hence, structural and stratigraphic characteristics of geologic units and the hydrodynamics of percolating or flowing groundwaters must prominently occupy the minds of planners, designers, and managers of waste disposal and management systems. Unfortunately, at present, this has not been the case, particularly in developing countries where pollution/contamination is becoming more commonplace. Even though those in developed countries now consider geologic and hydrogeologic effects, it has been late in coming, and pollution has ravaged many areas, precipitating devastating losses in financial, water, land, and human resources. Even with graphic examples that illustrate the consequences of poor planning, many plan-

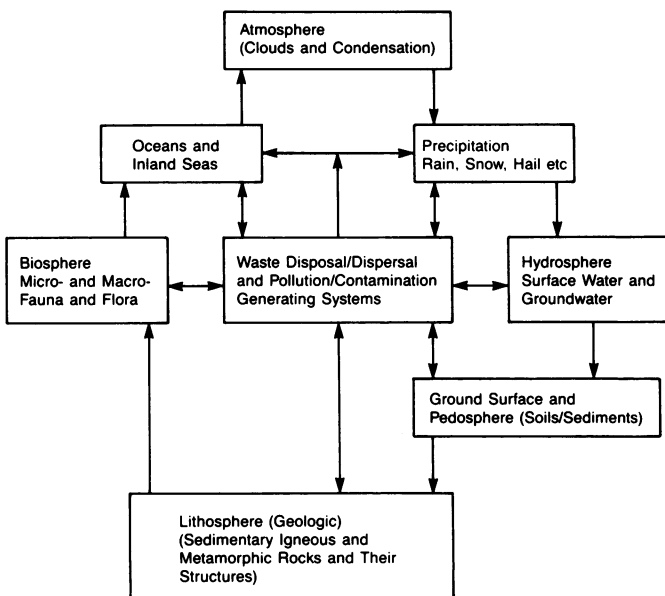


FIGURE 5. The hydrogeopollution cycle.

ners and managers are still skeptical about the role of geology in environmental pollution. At the same time, the lack of consideration of geologic, pedologic, and hydrologic/hydrogeopollution cycles has not been fully appreciated in developing countries. There does not seem to be enough consciousness given to understanding the implications of these cycles. Because of this, no priority is given to examining the impact of pollution incidences and the consequences of spread in the hydrogeologic environments.

Processes and Activities Generating Pollutants/Contaminants

Various processes, some of which may be manmade or anthropogenic, generate pollutants and contaminants that enter groundwater flow systems. These processes include physicochemical weathering, mass wasting, erosion, sediment transport, and deposition; agricultural activities; mining, mine-waste disposal, and acid mine drainage problems; oil exploration, exploitation, and gas flaring; other industrial activities such as manufacturing, distribution of manufactured products, arms, and armaments, etc.; sewage treatment, disposal, and management; runoff, floods, and snowmelt; biological pollution of wetlands and impounded reservoirs; saline lakes, ponds, and evaporite deposits; geothermal springs and mineralized waters; atmospheric fallout and rainout; burial grounds, garbage dumps, landfills, etc. Some pollution sources in rural environments that are usually ignored, even though they may be hazardous, include pit latrines, open-space communal toilets, widescale and indiscriminate uses of the bush for defecation, personal hygienic uses of water for washings, etc., microbiological activities (bacteria, virus, fungi, worms, etc.), radioactive material, and thermal products, heavy metals, trace elements, ions, etc.

Chemical Pollutants/Contaminants of Groundwater

Many developing countries are witnessing a stage of development where groundwaters from shallow wells and boreholes are gradually supplementing the original source of drinking water (surface water). The preference for groundwater to surface water is borne out of the belief that when surface water has been distributed as tap water it must always be subjected to some purification prior to distribution. Although surface waters are easily accessible where they exist in lakes, rivers, streams, and springs, many people believe that water wells produce water of excellent quality. Thus, groundwater is not treated before use and is believed to be free from pollution.

One place where one can find groundwater about as pure as rainwater is under a bare dune made of pure quartz sand (32). The water under quartz sandstone is clean and pure because quartz is so insoluble in water that for practical purposes, it is inert and neither soil

nor vegetation contributes dissolved substances to the groundwater it contains. Areas of pure quartz sand dune are few. Most surface soils and water-bearing formations are not pure quartz sandstone. A sandstone is made up of soil particles of different mineralogy. These particles are bound together by cementing materials, which are generally calcite, hematite, or silica. In contrast to quartz sand, surface materials of soils, limestone, shale, and other lithologic types react with percolating and infiltrating water to produce dissolved materials that pollute groundwater (Figs. 4 and 5).

Any groundwater system may be naturally polluted or contaminated to a certain degree at all times. The concern of many water resource planners and managers is whether the amount of measured pollutants are within the acceptable limits of water quality. The number of chemical pollutants and the degree of chemical pollution/contamination of groundwater depend on the geology, pedology, and the mineral composition of the soil and rock through which the water flows before reaching the aquifers. Groundwaters may have pollutants that not only depend on the pedology, geology, and mineralogy of the formations it flows through but also on the constituent pollutants/contaminants in the water that recharges the groundwater.

Recharge water, on the other hand, may be contaminated by atmospheric fallout, industrial and domestic wastes, etc. The type of physical, economic, agricultural, and social activities of the people living in a groundwater recharge area (Fig. 6) may affect its water quality. Thus, urban planners and managers must be wary of human activities that occur in recharge areas of aquifers in urban and rural areas. This is one of the main avenues by which pollutants or contaminants enter the groundwater. Hydrogeologic maps of the areas are lacking or have not been produced, so the recharge areas are not identified. This problem affects both developed and developing countries. Massive pollution of groundwater systems is a common occurrence because wastes are recklessly deposited on top of recharge areas.

Groundwater pollution is an ever present risk in developing countries, particularly in areas of mining and extensive industrial activities. This must constantly be in the minds of those responsible for water supplies in these areas. Borehole waters must, as a rule, be analyzed for chemical contaminants before the water is distributed and supplied to households. Unsatisfactory color and taste are easily detected and are good indicators for groundwaters of poor quality. Some groundwaters taste of iron, others may have a disagreeable odor. Such groundwaters should be avoided and not used for domestic purposes. Water containing only several parts per million of sodium and chloride ions tastes slightly salty. Lead and sulfur are distasteful when present in appreciable quantities in water. Conversely, however, some toxic elements have no taste, but when present in very small quantities may be dangerous to health. Very small concentrations of poisonous trace elements such as lead, arsenic, mercury, cyanide, and boron must

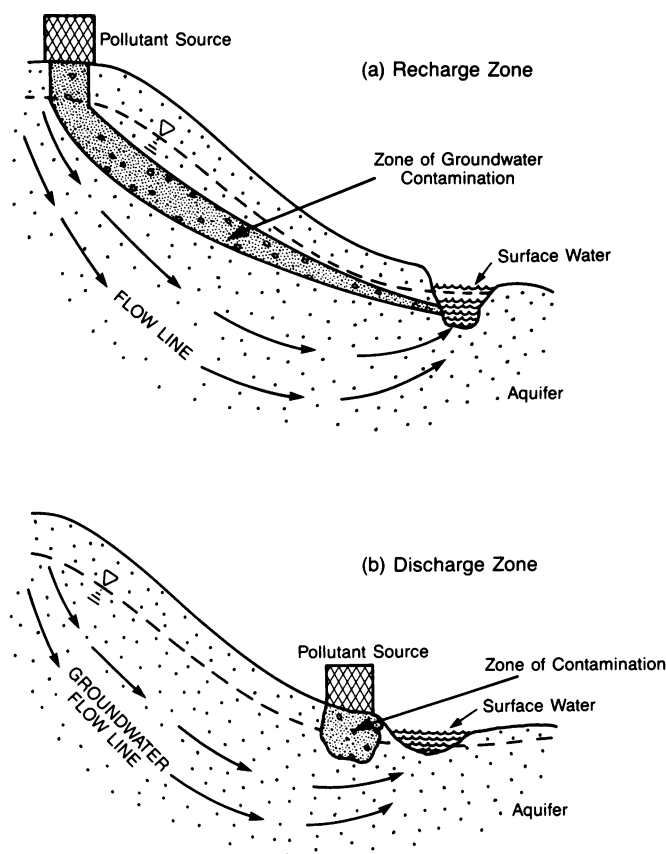


FIGURE 6. Schematic illustration of the extent of groundwater contamination for pollutants entering (a) recharge and (b) discharge zones.

be carefully documented. Water sampling and monitoring may reveal their presence.

The three components of water quality are bacteriological quality, physical quality, and chemical quality. Filtration and sedimentation processes take care of the physical quality. In practice, groundwaters are filtered by natural processes as they pass through columns of soils, sands, strata, or sedimentary layers of rocks. Groundwaters are usually clear of solid materials as they come from the aquifer, particularly if they are deep-seated ones. The intricate pore spaces or water passageways of the aquifer materials act as a fine filter and remove small particles of clay or any other fines. Organic materials decay or are destroyed in transit. Thus, the dirtiest and most polluted sewage water may become clear of suspended/particulate solid materials once it has gone through a thick bed of sand or geologic and pedologic units. As a result of this natural self-cleansing of polluted water by deep-seated aquifers, physical and some biological aspects of pollution may not pose serious problems in groundwaters.

Bacteriological quality of groundwater is taken care of by treatment with various chemicals that kill bacteria. Dissolved geochemical constituents, on the other hand, are difficult to remove entirely. They may be

removed through filtration in charcoal, through cation exchange, precipitation, dissolution, degassing, etc. The treatments may be expensive and may result in the creation of new pollutants and contaminants and their introduction into the treated waters. In developed countries, waters supplied for public use are routinely analyzed to certify that the content of toxic elements or contaminants are below mandatory limits. In many developing countries, groundwaters and even surface waters are often distributed to various communities untreated. In general, it is wrongly believed that exploited groundwaters are free of pollution. Emphasis is usually placed on water supply and quantity, and minimal priority is given to water quality and treatment. This is the main cause of outbreaks of epidemics of waterborne diseases in many developing countries because untreated surface water and groundwater are consumed by the people, particularly in rural areas, without water treatment. Since there are no monitoring programs, it is not possible to detect incidences of pollution.

The most undesirable trace elements-pollutants in groundwater are mercury (Hg), lead (Pb), cadmium (Cd), arsenic (As), barium (Ba), boron (B), cyanide (CN), selenium (Se), chromium (Cr), uranium (U), sulfur (S), and nitrogen (N). The United States Food and Drug Administration has specified the lower mandatory limits of these elements in domestic water. In addition, there are internationally accepted water quality guidelines for concentrations of these elements in water for various uses. Most groundwaters may also contain many major inorganic elements, compounds, and ions in excess of acceptable standards, such as iron oxide (Fe_2O_3), manganese (Mn), calcium (Ca), magnesium (Mg), chloride (Cl), aluminum (Al) and silica (SiO_2). Anions and cations can be found in their dissolved states. Temperature, where high, affects the properties of groundwater, especially the solubility of minerals. Deep groundwaters contain more chemical elements dissolved in them than do shallow ones. Very deep, hot groundwaters may be objectionable because they contain very high concentrations of these mineralized elements dissolved out of rocks by the high temperatures. This is characteristic of hydrogeothermal regions.

Groundwaters in limestone or Karstic terrains may contain dissolved calcium and magnesium salts. These salts make water hard. Hardness in excess affects taste and soap consumption in laundry. Temporary hardness is caused by carbonates and bicarbonates of calcium and magnesium; permanent hardness is caused by sulfates, chlorides, nitrates, and silicates of calcium and magnesium. The combination of both of these groups of substances gives total hardness. Hard water may also have a slight taste that is caused by other ions in solution.

A few groundwaters naturally become softened as they pass through and react with geologic formations containing zeolite minerals, which remove calcium and other ions. Zeolites and hydrous silicates chemically exchange certain ions from water for other ions bound in the solids. If, for example, water carrying calcium ions travels through a zeolite formation that exchanges Na^+

for Ca^{2+} , the water comes out with sodium instead of calcium and the zeolite becomes richer in Ca and poorer in Na.

Iron in water gives a bitter taste and makes water reddish or brownish in color. It is found in the form of bicarbonates and sulfates. Iron in groundwater is due to the presence of hematite below the ground surface. Iron is soluble in water containing carbonic acid. Water containing high iron is unsuitable for laundries, paper mills, film industries, etc.

Manganese acts in a manner similar to iron. It produces an undesirable taste, and white clothes washed in water containing manganese or iron turn yellow or brown. In small concentrations, Mn affects odor. Iron and Mn in water precipitate and produce undesirable turbid yellow-brown water that stains laundry. These elements support growth of microorganisms in distribution systems. These growths can accumulate and reduce the carrying capacity of pipes and clog valves. Small concentrations of Fe and Mn impart a metallic taste to water. Groundwater supplies contain more Mn and Fe than surface waters.

Excess carbon dioxide in water makes water corrosive to metals. It can be present in the form of carbonic acid, bicarbonate, carbonate or as free carbon dioxide (CO_2). Groundwaters drawn from great depths are deficient in dissolved oxygen (DO). Shallow groundwaters are usually saturated with dissolved oxygen. Hydrogen sulfide (H_2S) makes water unpalatable because of bad odor and taste. It is found in groundwaters where sulfide minerals such as galena, pyrite, sphalerite, etc., are present. Other dissolved gases in addition to CO_2 , DO, and H_2S that may cause pollution problems in groundwater include nitrogen dioxide (4,33), methane (31), and sulfur dioxide. They cause degrees of hazard in hydrogeologic systems that are functions of concentration but are hazards that can be removed during water treatment processes.

Geologic and Hydrogeologic Settings

Geologic Settings

Natural geological processes are primary contributors to groundwater pollution. In this regard, the rocks of the earth's crust are the major contributors of groundwater pollutants (Figs. 1 and 5). These contaminants are mostly minerals, gases, and the toxic elements they contain. A good understanding of the origin, occurrence, and distribution of these undesirable elements is essential for people concerned with the development of surface water and groundwater resources. Contaminants enter groundwaters from the recharge areas of aquifers. It is therefore very necessary to know the geology and mineral distribution in recharge areas of aquifers. Groundwater that is recharged from mining areas, fertilized agricultural farmlands, and industrial areas may not be safe for human consumption unless the recharge area is protected. Rain and surface water

can leach pollutants from mine dumps, ore deposits, city dumps, and fertilizer applied to farm lands into the recharge areas for groundwater supplies (Fig. 6).

Groundwaters recharged from polluted areas must either be avoided or pollution sources checked and monitored very carefully. The geology of recharge areas of aquifers influences the quality of groundwater. The number of pollutants and the degree of pollution in groundwaters depend on the geology and the mineralogical compositions of the rocks through which the water flows. Groundwaters may also acquire pollutants and contaminants as they flow across different geological and mineralogical zones or units of formations. Chemical reactions between the water and rock fragments in the soil and numerous chemical and physicochemical reactions between water and rock in the groundwater environment alter the composition of the groundwater. Surface waters recharged by surface water draining through limestone areas may be hard and need considerable softening treatment before being supplied for domestic and industrial use. Rainwater absorbs carbon dioxide in the air, forming carbonic acids, which react with limestone, liberating bicarbonates and carbonates which, when added to percolating groundwaters, make them hard. Surface materials of soils and shale react with rain to produce dissolved materials that contribute to the taste and color of groundwaters. The taste and color of such waters depend on the composition of the rocks through which the water passes. Surface waters draining metamorphic areas containing talc dissolve magnesium salts that contribute to the hardness of groundwater.

Surface water draining areas of sulfide mineralization introduce sulfur and many other metallic ions into groundwaters. The chemical characteristics of groundwater vary greatly as a result of the diversity of rock materials through which the water passes. Sedimentary rocks provide the largest aquifers and water passing through such rocks acquire considerable concentrations of chemical components of these rocks. Carbonate rocks, such as limestone and dolomite dissolve easily in acid water with the result that water in contact with these rocks are high in calcium and magnesium bicarbonates. In igneous and metamorphic terrains, groundwater occurs in weathered parts of the basement rocks or faults, joints, and fissures. Rainwater percolating through these fissures dissolve many soluble elements. The groundwater in basement areas may be contaminated by ions dissolved from the basement rocks (Fig. 3).

Weathering and oxidation of basement rocks create a favorable acid environment for mobilization of many metals. Weathering and fracturing of basement rocks also create porosity necessary for storing water. Consider a granite containing about 5 ppm of uranium in solution. During weathering uranium will be oxidized to the soluble uranyl oxide in the near surface weathering environment. The oxidized uranium is then mobilized and dissolved in shallow groundwater in the basement area. Data from Trentham and Orajaka (34) and Orajaka (35) show that significant amounts of ura-

nium are leached and mobilized from felsic igneous rock by carbonic acid water. A significant quantity of uranium is leached from the albite-riebeckite-granite in Kaffo Valley, Northern Nigeria, during weathering of the roof of the granite mass (36). This example illustrates how abnormally high uranium and other major, minor, and trace elements are leached and introduced into shallow groundwaters in the veins, fissures, and porous parts of basement rocks.

It is thus important to test all shallow groundwaters in basement or hard rock areas for metal contamination before supplying such water to homes and industries. In many developing countries, rural dwellers obtain their water from shallow, hand-dug wells (37). In most cases where the water is tested, they are usually contaminated, particularly for shallow wells in urban centers situated in basement rock areas. Toxic metals, notably Pb from weathering products of ores in mineralized veins of faults and fissures, can enter natural water systems. The metal concentrations are abnormally high for water descending through fissures exposed during mining operations. These contaminated waters find their way into groundwaters, thereby polluting them. Surface water and floods in the Pb-Zn mineral belt of southeastern Nigeria contain high concentrations of Pb-Zn. These metal ions are also present in shallow groundwaters in the area. The high Pb content of the shallow groundwater have posed some serious health problems. Their implications and extent of hazards are yet to be fully investigated.

Structural Features and Sedimentary Characteristics

The structural and sedimentary properties of rocks that affect groundwater quality include layering, fractures, joints, faults, and shear zones (Figs. 2 and 3). These structural features act as hosts for mineralizations and also serve as channel ways that conduct surface waters to aquifers. Faults, shear zones, and joints are often mineralized. The most common veins and fissure-filling minerals are sulfides. Oxygen-laden surface waters and carbonic acid waters entering these fissures oxidize and dissolve cations and anions from the sulfide minerals and introduce them into shallow groundwaters. The toxic metallic elements introduced into the groundwater by this method include As, Cs, Hg, Pb, Ni, etc. Thus, in the surface or subsurface disposal of wastes, the structural, stratigraphic, and sedimentological natures of the area must be mapped, described, and known in order to produce a waste management design that would contain the wastes safely and keep these toxic elements from migrating into surrounding surface waters and groundwaters.

Hydrogeologic Settings

Because contaminants are transported in large part by the bulk motion of groundwater, the parameters of groundwater flow are of major importance in the un-

derstanding of contaminant processes. The various aspects of the groundwater environments, as well as stratigraphic factors that control or could influence groundwater motion, are also of major consideration. The hydrogeological environment is shown schematically in Figures 2 and 4. It consists mainly of the saturated and unsaturated zones. The unsaturated zone occurs above the capillary fringe where the soil pores are partially saturated with water. This zone is important in waste management because in most cases, it is the burial zones for wastes. Consequently, a thick unsaturated zone may sometimes be preferred for waste disposal since it would take a much longer time for contaminants to reach the water table. In the saturated zone, the pores are saturated with water. When this zone is capable of transmitting significant quantities of water for economic use it is referred to as an aquifer. In most field situations, two or more aquifers occur, separated by impermeable strata or aquitards. In the situation illustrated in Figure 2, the upper or unconfined aquifer is much more prone to pollution than the lower confined aquifer.

Fluid motion in saturated geological materials is dependent on the hydraulic gradient, porosity, and hydraulic conductivity. Average groundwater velocity \bar{v} is obtained from the relation (38),

$$\bar{v} = -\frac{K}{n} \frac{dh}{dl}; \quad i = \frac{dh}{dl} \quad (1)$$

where $i(dh/dl)$ is the hydraulic gradient, n is the porosity, K is the hydraulic conductivity, and dh/dl is the change in hydraulic head (h) with respect to the change in distance (l). Porosity and hydraulic conductivity, in particular, are properties that are dependent on the geologic conditions of the waste disposal site. Differences in hydraulic conductivity values across a stratigraphic section could appreciably determine whether flow is upward, downward, or horizontal, as demonstrated by Freeze and Witherspoon (39). Thus, the ultimate fate of contaminants emanating from waste disposal sites can be strongly dependent on whether groundwater flow is upward or downward. Therefore, the direction of flow of groundwater is an important factor in the evaluation of sites for waste disposal. The actual magnitude of groundwater velocity is also an important factor. In low permeability geological materials, groundwater velocity can be as low as a few centimeters per year. For such conditions, contaminants would be transported over very short distances over a very long time span and hence may not pose hazards to the environment.

In contrast to the low velocity of groundwater that occurs in low permeability materials such as shales, the velocity in permeable deposits or fractured media can be quite large. High groundwater velocity zones provide a pathway through which water supply sources become quickly polluted. The search for and the evaluation of such high-velocity pathways is therefore an important task in the groundwater pollution studies. The ease and

extent to which contaminants can pollute an aquifer are also dependent on whether the contaminants are introduced into the groundwater system at the recharge or discharge areas. Figure 6 shows that a major portion of an aquifer may become contaminated if the contaminant is introduced into the subsurface from an upland recharge site. Hence in designing or planning a waste disposal site, the entire hydrogeological properties of the area must be well established to ensure a safe and long-lasting disposal network.

Contaminant Pathways and Processes in Groundwater Systems

Pathways of entry of contaminants into groundwater systems depend largely on patterns of waste disposal and human interferences with the environment. An understanding of the general methodologies of waste disposal is thus a prerequisite to any discussion of contaminant pathways into the subsurface environment. The various waste disposal options currently in use include sanitary landfills, open dumps, septic tanks and cesspools, and deep well injection systems.

Sanitary Landfills and Garbage Dumps

Much of the solid waste that is now disposed of on land is placed in sanitary landfills. In humid areas, in particular, buried waste in sanitary landfills and dumps is subject to leaching by percolating rainwater. The leaching process is accompanied by chemical reactions that tend to consume all available oxygen, while releasing carbon dioxide, methane, ammonium, bicarbonate, chloride, sulfate, and heavy metals. The liquid mix of these constituents is referred to as leachate. The total number and chemical concentrations of these constituents can be variable depending on the initial composition of the waste climatic conditions. Table 5 shows that leachates contain large numbers of inorganic contaminants and also have high total dissolved solids. Leachates also contain many organic contaminants. Robertson et al. (40), for example, identified over 40 organic compounds in leachate samples (contaminated groundwater in a sandy aquifer in Oklahoma). Leachates emanating from landfills contain contaminants and toxic constituents derived from solid wastes, as well as from liquid, industrial wastes placed in the landfill (41).

Rain water percolation through refuse in the landfill causes water table mounding, i.e., a rise in water table elevation within or below the landfill. The mounding process, according to Freeze and Cherry (38) causes leachate to flow downward and outward from the landfill, as illustrated in Figure 7. Thus, for shallow aquifers, in particular, water table mounding provides a pathway for the entry of contaminants into the groundwater system as a result of the buildup in hydraulic gradient and pressure head.

Septic Tanks and Cesspools

Septic tanks are designed to remove settleable solids, reduce biochemical oxygen demand, eliminate micro-

Table 5. Representative ranges for various inorganic constituents in leachate from sanitary landfills (36).

Parameter	Representative concentration range, mg/L
K ⁺	200–1000
Na ⁺	200–1200
Ca ²⁺	100–3000
Mg ²⁺	100–1500
Cl ⁻	300–3000
SO ₄ ²⁻	10–1000
Alkalinity	500–10,000
Fe (total)	1–1000
Mn	0.01–100
Cu	< 10
Ni	0.01–1
Zn	0.1–100
Pb	< 5
Hg	< 0.2
NO ₃ ⁻	0.1–10
NH ₄ ⁺	10–1000
PO ₄ ³⁻	1–100
Organic N	10–1000
Total dissolved organic carbon	200–30,000
Chemical oxygen demand	1000–20,000
Total dissolved solids	5000–40,000
pH	4–8

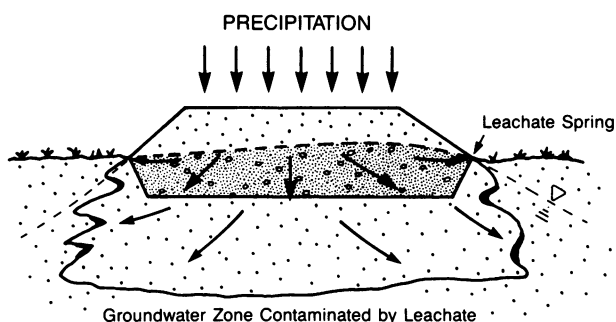


FIGURE 7. Water table mound beneath a landfill, causing migration of contaminants deeper into the groundwater zone (38).

organisms before (the treated) sewage is released through a drainfield into the ground. A generalized diagram illustrating the layout of a septic tank waste-disposal system is shown in Figure 8. The figure demonstrates that septic tank system effluents can quite easily reach and contaminate the groundwater system. According to the United States Environmental Protection Agency (42), septic tanks and cesspools are the largest contributors of wastewater to the ground and are the most frequently reported sources of groundwater contamination in the United States.

Apart from the effluent that is directly released into the ground, there are large volumes of solid residual materials known as sewage sludge. In many parts of the world, this sludge, which contains a large number of potential contaminants, is applied on agricultural lands to enhance crop nutrients such as nitrogen, phosphorous, and heavy metals that are needed for plant growth. Although this practice actually improves soil fertility, it has been observed that one of the potential

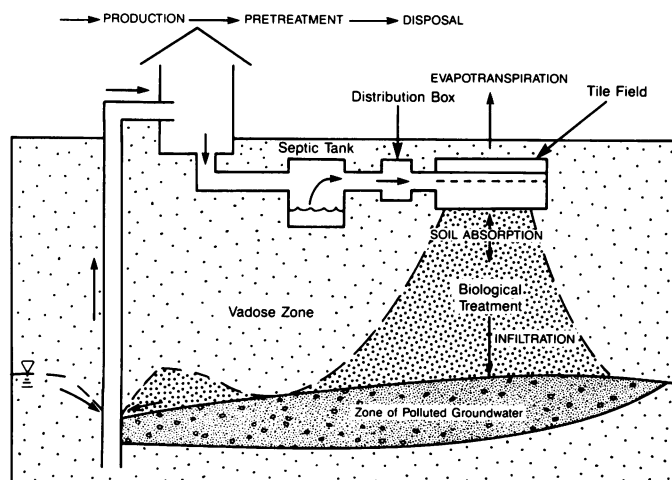


FIGURE 8. Contamination from a septic field (57).

negative impacts of this type of sewage disposal is degradation of groundwater quality (38). Contaminants in the sewage sludge/effluent reach and contaminate groundwater through infiltrating water from rain or snow.

Radioactive Waste Disposal

Radioactive wastes are generated at various stages in the nuclear industry. Mining and milling of radioactive ores result in the production of large volumes of waste rock and tailings. Nuclear plant operation generates radioactive fission products, reactor cooling waters, irradiated fuel rods, and other by-products.

Figure 9 illustrates several types of waste burial alternatives. In all cases, the wastes are stored in strong, engineered concrete containers. In the option illustrated by Figure 9a, the containers are placed on the surface of the ground and then covered with earth materials. Figures 9b and 9c illustrate the options in which the containers are placed a few meters below the surface of the ground either below or above the water table. The difference between these two options is that in the latter (Fig. 9c) the fill in the excavation is designed to provide enhanced containment capability for the system. A large number of burial options for radioactive wastes in Canada and the United States are in the category represented by Figure 9b (38). In Figures 9d and 9e, the containers are buried in large holes about 10 to 20 m deeper than in the previous examples.

Because of the highly lethal nature of radioactive wastes, particularly for those with long half-lives, it is necessary that these wastes are disposed of in systems that have high containment capability. Failure of the burial sites could result in the leakage of radioactive materials into the groundwater environment or into the biosphere. To avoid problems of subsurface radionuclide migration, numerous reported investigations including Cherry et al. (43) have suggested that burial sites should have the following characteristics: geomorphic and

structural stability, isolation from fractured bedrock, absence of subsurface flowlines that lead directly to the biosphere or to subsurface zones of potable water, low measured or predicted radionuclide velocities, and water table conditions that are deep enough to permit waste burial to remain entirely in the unsaturated zone.

Deep-Well Disposal

Disposal of liquid wastes of industrial origin by injection into the deep underground is a widely accepted practice. The growing acceptance of this waste disposal option is mainly due to the numerous problems of pollution in near surface hydrologic environments (44). The growing acceptance of this option is suggested by the results of a survey conducted by Warner and Orcutt (45), which showed that waste injection wells increased from 30 in 1964 to at least 280 in 1973 in the United States. There are now more than 100,000 of these wells in North America. Although deep-well injection of liquid wastes is meant to minimize the problem of pollution in the near surface hydrologic environment as suggested by Piper (44), the potential for pollution of deep-seated aquifers is still obvious. If the pollution of deep-lying aquifers is to be avoided, the disposal option requires the isolation of formations receiving waste injections from permeable contact with other elements of the hydrologic environment.

Human Activities and Pollution/Contamination

Contaminants can be introduced into the groundwater system as a result of myriads of human activities. This category of contamination of groundwater systems differs from the ones described earlier in that such human activities do not *ab initio* introduce wastes into the subsurface. The major human activities that eventually end up polluting groundwater systems include agricultural activities, storage of gasoline tanks in the subsurface, pipe lines, road deicing, mining and pumpage of aquifers, etc.

Nitrate loading of shallow groundwater systems arising from fertilizer application occurs mainly through leaching. Where there is significant downward flow, deep-seated aquifers can become affected. According to Freeze and Cherry (38), widespread nitrate contamination of aquifers through fertilizer application is rare. Numerous investigators including Grisak (46) and Custer (47) have shown from case studies in various parts of the United States and Canada that nitrate derived by oxidation and leaching of natural organic nitrogen in the soil is more often responsible for extensive nitrate contamination of shallow groundwaters. The pathway down to the water table of those contaminants generated through mining activities and road salt application is similar to that for nitrates, i.e., they reach the water table through leaching and flushing through the unsaturated zone by infiltration of percolating water from rain and snowmelt.

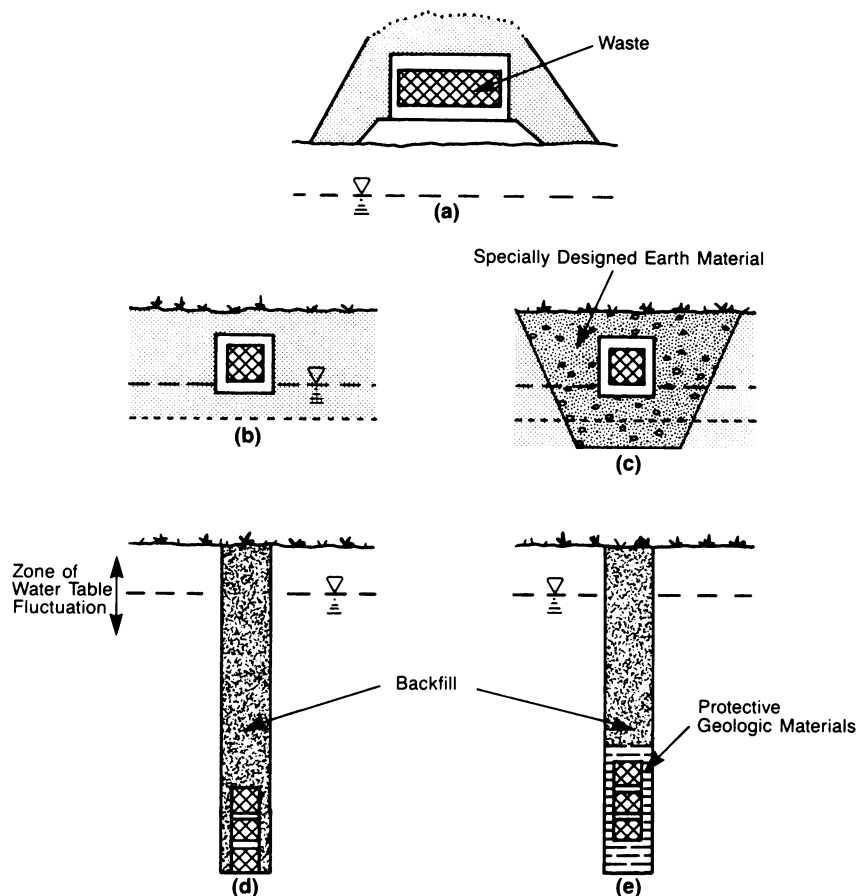


FIGURE 9. Schematic diagrams illustrating methods of disposal of radioactive wastes (38).

Petroleum leakage from underground storage tanks and oil pipe lines, as well as spills from oil-producing wells, constitute an increasing threat to groundwater quality (Fig. 10). Petroleum contaminant pathways into

the groundwater system are illustrated in Figure 10. A simple hydrogeologic condition is assumed. According to Freeze and Cherry (38), in the initial migration stage (seepage stage), the oil moves primarily in a downward

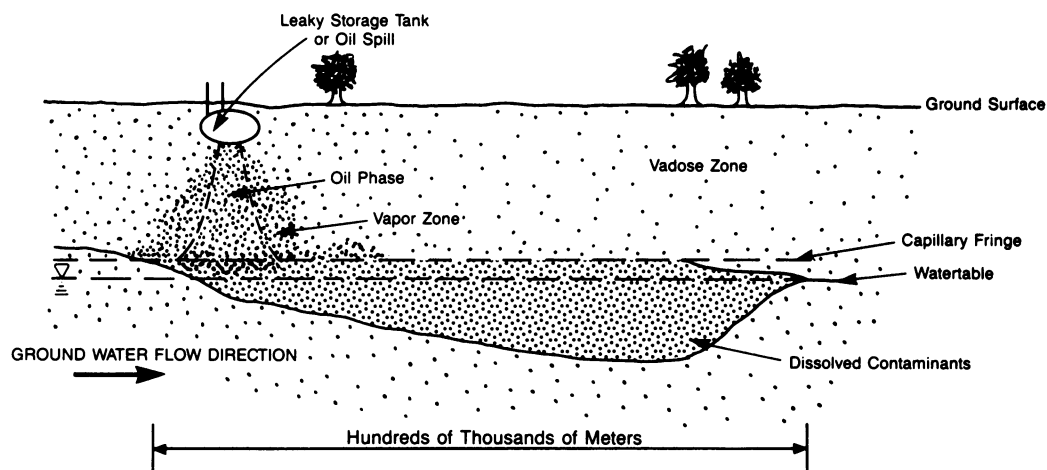
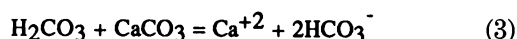
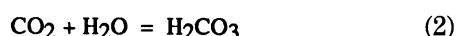


FIGURE 10. Contamination from a leaky storage tank or oil spill (57).

humic acids. In that case, their mobility will be reduced. It is thus concluded that adsorbing and nonadsorbing ligands may compete for contaminant ions and thus determine, on the basis of the relevant formation constants, the distribution of complexed contaminants between adsorbed and solution states.

Acid-Base Reactions

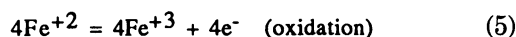
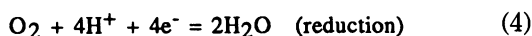
Acid-base reactions are those chemical reactions involving the transfer of protons. Proton activity, H^+ , expressed as $-\log H^+$, is referred to as pH. The numerical value of pH gives an indication of the acidity of natural waters. The pH of natural waters is controlled by calcite ($CaCO_3$) dissolution and the CO_2 in the soil zone according to the following equations:



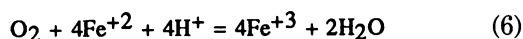
According to Stumm and Morgan (49), $CaCO_3$ is an efficient pH buffer only in the neutral and acid pH range. In the pH range of 9 and above, the incongruent dissolution of aluminosilicate minerals provides a greater buffer capacity. In pollution studies, it is important to know the pH of the groundwater and its buffering agents since the solubility of many minerals as potential contaminant sources and sinks are dependent on pH. Acid-base reactions become prominent in environmental pollution and degradation where situations create extremes of acidity or alkalinity. Thus, in acid mine drainage areas, acid rain, alkalinity, or alkaline rain situations, the hydrogeological processes such as oxidation-reduction, cation exchange, adsorption-desorption, etc., may result in the ultimate release of pollutant and contaminants into these systems to damage them.

Oxidation-Reduction Processes

Oxidation-reduction (or redox) processes are of a major importance in governing the geochemical behavior of those elements that may gain or lose electrons in groundwaters. By definition, oxidation is the loss of electrons and reduction is the gain in electrons, as shown in the following illustrated examples for the oxidation of iron:

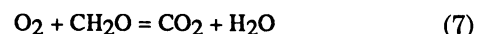


In reality, a reduction reaction is coupled to the corresponding oxidation reaction, so that the overall redox reaction for the oxidation of iron, for example, is of the form:



The redox state of groundwater is described by the redox potential pE (or Eh). Water infiltrating into shallow groundwaters has high redox potential due to its

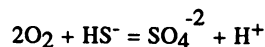
high dissolved oxygen content. Along the flow system, the tendency is toward oxygen depletion. The first stage in the oxygen depletion process is the oxidation of organic matter (CH_2O):



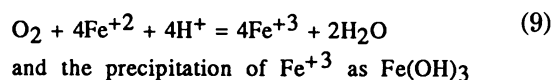
Reaction 7 is catalyzed by bacteria or isolated enzymes. They derive energy by facilitating the process of electron transfer. Organic matter oxidation of the type illustrated in Eq. (7) is a major redox reaction occurring in landfills and other similar waste disposal sites. Thus, leachates emanating from landfills have much lower redox potential. The leachates also have elevated concentrations of NH_4^+ , H_2S , Fe^{2+} , Mn^{2+} , and FeS .

As the leachate enters the groundwater system, the following sequence of redox processes would occur (38):

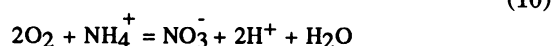
- (i) Oxidation of Sulfide to Sulfate, (8)



- (ii) Oxidation of Ferrous Iron,



- (iii) Nitrification

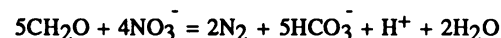


- (iv) Manganese Oxidation

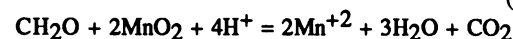


When all the dissolved oxygen in the groundwater is consumed, oxidation of organic matter can still occur as indicated in the following reaction equations (38):

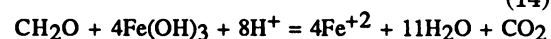
- (i) Denitrification (12)



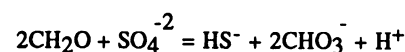
- (ii) Manganese (iv) Reduction (13)



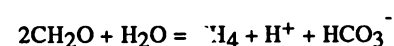
- (iii) Iron (iii) Reduction (14)



- (iv) Sulfate Reduction (15)



- (v) Methane Fermentation (16)



It is clear from these reaction sequences that adequate knowledge of the redox environment is needed for the purpose of predicting the mobility of those elements that have variable valences and which form low water-solubility oxides. For example, oxidized forms of iron [$\text{Fe}(\text{OH})_3$] and manganese (MnO_2) are highly insoluble; the reduced forms (Fe^{2+} ; Mn^{2+}), however, are soluble in water and thus move with the groundwater. Uranium, selenium, arsenic, and molybdenum are insoluble under reducing conditions and soluble under oxidizing conditions. Thus, depending on the physical, chemical, and biological conditions within the hydrogeochemical environment, contaminants may exist in polluted groundwater systems in various concentrations and forms. Detailed instrumentation and closely spaced monitoring programs easily delineate the geochemical zones (4,7,33,41).

Precipitation-Dissolution Reactions

Precipitation-dissolution reactions are a set of reactions by which contaminants may be removed from solution either by direct precipitation or by isomorphous substitution with an ion of similar atomic radius in a crystal that is forming or that has formed (48). The formation of metal carbonates, e.g., $\text{Sr}(\text{CO}_3)_2$, $\text{Cd}(\text{CO}_3)_2$, provide good examples of removal of contaminants from solution in groundwater by precipitation reactions. Saturation index calculations may be employed to determine whether a mineral species is likely to dissolve or precipitate in a groundwater flow system (38).

Adsorption-Desorption Reactions

Adsorption occurs when a dissolved ion becomes attached to the surface of a preexisting solid substrate (50). In porous media, contaminants can become adsorbed onto colloidal-size particles. The adsorption capacity of colloids is thought to be due to their ability to generate a charged solid-solution interface. The presence of a solid surface charge arises from imperfections or ionic substitutions within the crystal lattice of the colloids. The charge imbalance arising from the accumulation of charge on the colloid surface, however, is compensated for by a surface accumulation of ions of opposite charge known as counterions. Ion exchange occurs when the ions in the counterion layer become exchanged for other ions. Cation exchange capacity has been defined by Jackson and Inch (48) as the excess of counterions which can be exchanged for other cations in the bulk of the solution. It is usually expressed as the number of milliequivalents of cations that can be exchanged in a sample with a dry mass of 100 g. Cation exchange reactions are important in the predictive analysis of the mobility of contaminants in geological media. A measure of the mobility of contaminants that is used in predictive analysis is the distribution coefficient (K_d). It is defined as "the number of milliequivalents of an ion adsorbed per gram of exchanger divided

by the number of milliequivalents of that ion per milliliter remaining in solution at equilibrium" (48). The magnitude of the distribution coefficient is a measure of the extent of partitioning of a contaminant species between the solid and liquid phases along a groundwater flow system.

Microbial Reactions

Most of the geochemical reactions leading to the breakdown and transformation of complex molecules in groundwater systems are microbially mediated. These microorganisms derive energy and constituents needed for survival from these reactions. For bacteria to function and proliferate, it is also important for suitable temperatures and pH conditions to prevail in the medium (48). In the investigations carried out by Jackson and Inch (48), it was also observed that bacterially mediated chemical processes may have either beneficial or detrimental effects on particular pollutants. The beneficial effects include purification of contaminated water as organic pollutants are broken down into substances such as CO_2 , H_2O , NO_3^- , and SO_4^{2-} . Elements such as N, S, C, and P are used in the synthesis of microbial protoplasm and are thereby removed from the groundwater system. Among the detrimental effects is the depletion of dissolved oxygen.

Two phases are involved in the infiltration of unpolluted groundwaters by polluted surface waters. These are associated with the oxygen-rich unsaturated zone and the oxygen-deficient zone which is usually saturated. Organic pollutants are usually removed by filtration in the unsaturated zone where an effective biological filter can be formed. By these processes some soils constitute an efficient filter for water treatment. Most microorganisms are not adapted to this tortuous and highly competitive environment, which limits their movement to no more than 3 m in depth (51). For this reason, any well or borehole not properly lined for its entire length stands a chance of being polluted by microorganisms from surface waters.

Adsorption is the main mechanism by which microorganisms are removed from the oxygen-depleted saturated zone. Under this condition, microorganisms may be carried passively in groundwaters up to a distance of 30 m horizontally (51). In view of this, a minimum protection zone of 30 m is essential in siting boreholes and wells if contamination from polluted surface water from septic tanks, agricultural wastes, and refuse tips is to be avoided. Fissured rock strata constitute an additional problem. Where they exist, the extent of passive travel by microorganisms is unlimited, as natural purification through soil is almost nonexistent (52).

During hydrogeomicrobiological processes, the activities of nonpathogenic bacteria in groundwaters could be beneficial because they are involved in the degradation of detergents, herbicides, pesticides, and general mineralization, including cycling of essential elements, nitrogen, phosphorus, and sulfur. When pollution is in excess, these beneficial processes could lead to problems

for groundwaters, such as depletion of dissolved oxygen, reduction of nitrate to nitrite or ammonia, reduction of sulfate to sulfide with attendant offensive odors and growth of filamentous bacteria, reaction of sulfide with iron to form an insoluble precipitate that can restrict groundwater flow, and mobilization of iron from soil under conditions of reduced oxygen tension only to be oxidized and precipitated in other regions of the aquifer either by chemical or microbiological means (24). Under anoxic conditions, gram-negative chemolithotrophic bacteria utilize nitrates, sulfates, and iron/manganese oxides as terminal hydrogen acceptors in respiration and other physiological processes.

Contaminant Transport: Physical Processes

An accurate description of the spatial and temporal distribution of contaminants in groundwater systems is of major importance in groundwater pollution studies. The model widely applied in the evaluation of contaminant migration is based on the advection-dispersion equation. It is derived from considerations of mass flux into and out of a fixed elemental volume within the flow domain. The physical processes that control these fluxes are advection (i.e., contaminant transport due to bulk movement of groundwater) and hydrodynamic dispersion that accounts for the mechanical mixing and molecular diffusion within the flow system. Loss or gain of contaminant mass in the elemental volume results from chemical or biochemical reactions, radioactive decay, or combinations of these. The exact form of the advection-dispersion equation depends on whether the contaminants under consideration are nonreactive or reactive.

For nonreactive constituents, the one-dimensional form of the advection-dispersion equation in saturated, homogeneous, isotropic materials under steady-state uniform flow is (38):

$$\frac{\partial C}{\partial t} = D_x \frac{\partial^2 C}{\partial x^2} - \bar{v} \frac{\partial C}{\partial x} \quad (17)$$

where x is a curvilinear coordinate direction taken along the flowline, \bar{v} is the average linear groundwater velocity, D_x is the coefficient of hydrodynamic dispersion along the x direction, C is the contaminant concentration, and t is time. The coefficient of hydrodynamic dispersion is of the form:

$$D_x = \alpha_x |\bar{v}| + D^* \quad (18)$$

where α_x is the dispersivity, a characteristic property of the porous medium, and D^* is the coefficient of molecular diffusion. The term $\alpha_x |\bar{v}|$ expresses the mechanical mixing component of the dispersion process, which is the result of velocity variations within the porous medium.

The advection-dispersion equation is solved under prescribed boundary conditions. For the following boundary conditions:

$$C(x,0) = 0; \quad x \geq 0 \quad (19)$$

$$C(0,t) = C_0; \quad t \geq 0 \quad (20)$$

$$C(\infty,t) = 0; \quad t \geq 0 \quad (21)$$

the solution to Eq. (18) for a saturated homogeneous porous medium is given by Ogata (53) as

$$\frac{C}{C_0} = 0.5 \left[\operatorname{erfc} \left(\frac{x - \bar{v} t}{2\sqrt{D_x t}} \right) + \exp \left(\frac{x \bar{v}}{D_x} \right) \operatorname{erfc} \left(\frac{x + \bar{v} t}{2\sqrt{D_x t}} \right) \right] \quad (22)$$

where erfc represents the complementary error function and all other terms are as previously defined.

Figure 13 illustrates the concentration profiles obtained with Eq. (22) and what is normally referred to as a breakthrough curve for contaminants migrating through a porous medium. The figure demonstrates the effect of mechanical dispersion and molecular diffusion, namely that of causing some of the contaminants to move faster and others to move slower than the average linear groundwater velocity. This causes a spreading out of the concentration profile along the direction of flow and to some extent in directions transverse to it. In the absence of dispersion and diffusion, the contaminant front will move as plug flow, and its position along a flow system will be entirely determined by the average linear groundwater velocity.

In the case of reactive contaminants, a sorption term is added to Eq. (22) to account for the transfer to or from the solids in the elemental volume. The advection-dispersion equation then takes the form (38):

$$\frac{\partial C}{\partial t} + \frac{\rho_b}{n} \frac{\partial s}{\partial t} = D \frac{\partial^2 C}{\partial x^2} - \bar{v} \frac{\partial C}{\partial x} \quad (23)$$

where ρ_b is the bulk density of the porous medium, n is the porosity, and s is the mass of the chemical constituent adsorbed on the solid part of the porous medium per unit mass of solids; $\partial s / \partial t$ represents the rate at which

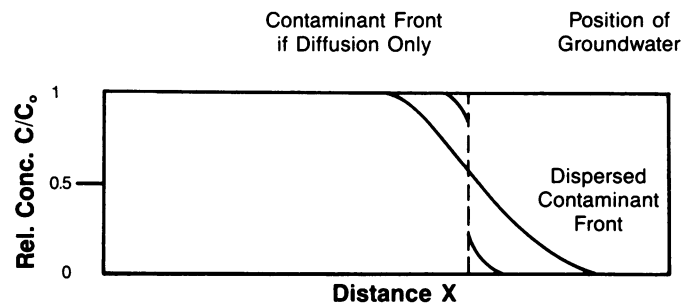


FIGURE 13. Schematic diagram showing the contribution of molecular diffusion and mechanical dispersion in causing spreading during contaminant migration (38).

the contaminant is adsorbed, and the term $(\rho_b/n) (\partial s/\partial t)$ represents the changes in concentration in the fluid phase caused by adsorption or desorption. If biochemical processes are ignored, the sorption term then depends only on ion exchange, precipitation and coprecipitation.

When a contaminant is adsorbed by a solid, it migrates at a rate slower than if there was no adsorption. Assuming a fast and reversible adsorption-desorption (cation-exchange) process, and if the concentration of the adsorbed contaminant is small compared with the total concentration of cations in solution, the rate of advance of the contaminant front is given by (50):

$$V_c = \frac{\bar{v}}{1 + \frac{\rho_b K_d}{n}} \quad (24)$$

where V_c is the velocity of the adsorbed contaminant and K_d is the distribution coefficient. The terms in the denominator are referred to as the retardation factor, which can be used to estimate how rapidly a contaminant would migrate through the flow system. The effect of retardation on contaminant migration is schematically shown in Figure 14. The contaminant front in the case of the adsorbed species, A^+ , moves at a much slower rate than that of the nonadsorbed species, B^+ . An important implication of this condition is that compared with a nonadsorbed species, it will take a much longer time for the adsorbed contaminant species to reach and pollute a groundwater supply source, and hence is less of a threat or hazard to the environment.

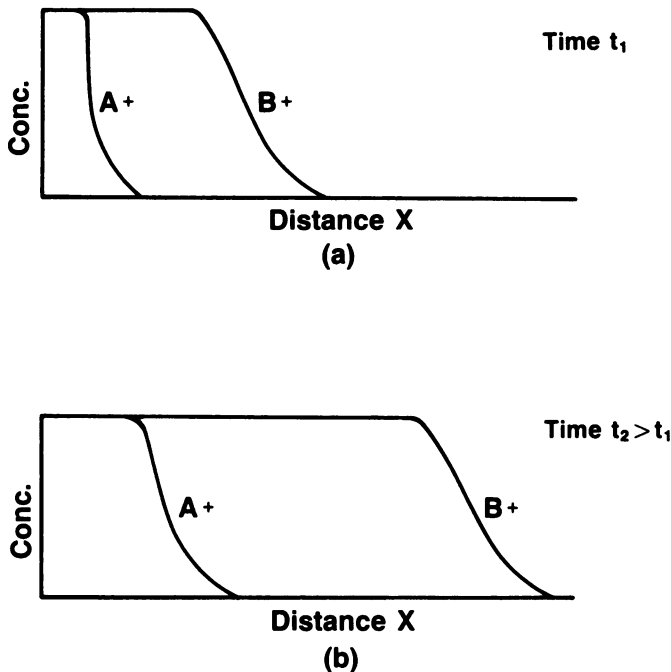


FIGURE 14. Schematic diagram showing the effect of retardation. The migration of an adsorbed species (A^+); the position of non-adsorbed species (B^+) (50).

Field Application of Advection-Dispersion Equation

An example of the application of the advection-dispersion equation in the solution of problems in contaminant migration is provided by a field study carried out by Egboka et al. (41). In the study, an analytical solution to the one-dimensional form of the advection-dispersion equation was used to simulate the distribution of tritium (a nonreactive species) produced during atmospheric testing and use of nuclear weapons along a contaminant plume under a landfill site in Borden, Ontario, Canada. Field values of radioactive bomb tritium were correctly simulated by using longitudinal dispersivity values of between 30 and 60 m and groundwater velocity values of about 10 m/year (Fig. 15). These aquifer parameters were used to predict the movement, spread, and dispersion of contaminants in the polluted groundwater such as sulfate (Fig. 16), chloride, etc. While Egboka et al. (41) investigated dispersion of contaminants introduced into the hydrogeologic system under natural conditions, Sudicky et al. (54) introduced artificial tracers into the same area and arrived at similar results usable for the planning and management of landfills and garbage dumps.

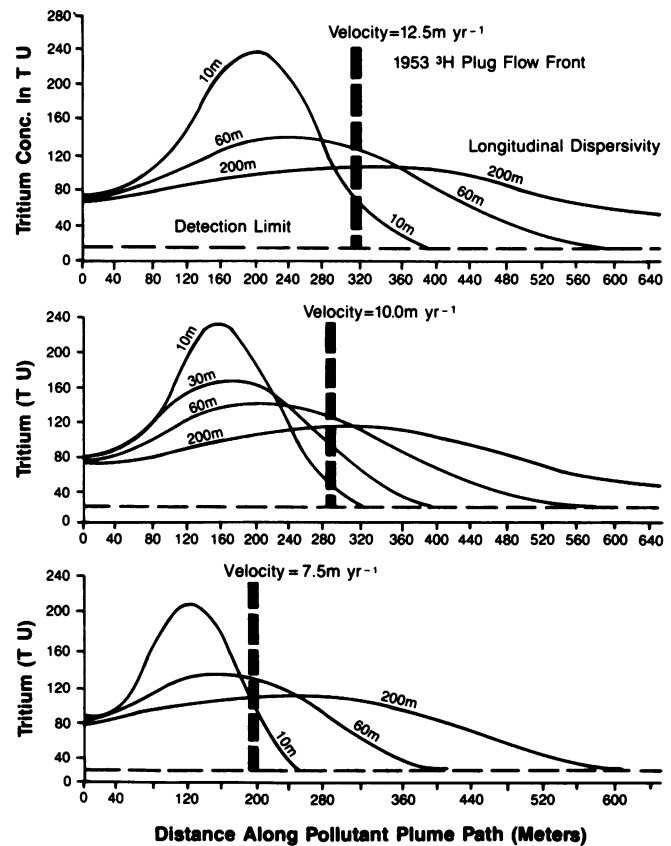


FIGURE 15. Simulated bomb ^3H versus distance in a landfill aquifer using varied velocities and longitudinal dispersivities (41).

Pollution Situation in Developed and Developing Countries

As a result of the ever-increasing industrial establishments and man's general activities, physical, chemical, and biological substances are being fed into the groundwater environment on a daily basis. This section summarizes the pollution situation in both developed and developing countries. Emphasis is focused on the developing countries.

Developed Countries

Groundwater literature is filled with incidences of groundwater pollution in many parts of the developed countries including the United States, Canada, USSR, and various parts of Europe. Table 6 presents a summary of groundwater contamination incidents in parts of the United States as reported by Lindorff (55). The number and percentage of incidents affecting or threatening groundwater supplies is shown in the second column. The third column shows the number and percentage of the cases that threatened or produced fires or explosions.

Table 6. Summary of groundwater contamination incidents (46).

Contaminant	No. of incidents	Water supplies, %	Fire or explosion, %
Industrial wastes	50	31 (62)	2 (4)
Landfill leachate	46	7 (15)	0
Petroleum products	27	18 (57)	10 (37)
Organic wastes	21	15 (71)	0
Chlorides	16	13 (81)	0
Radioactive wastes	7	2 (29)	0
Pesticides	4	2 (50)	0
Fertilizer	3	3 (100)	0
Mine drainage	3	1 (33)	0
	173	92 (53)	12 (7)

The ever-increasing use of organic pesticides and herbicides has constituted another source of groundwater contamination. Various investigators in the southwestern United States have observed that pollution by pesticides must be listed as an important potential hazard. Croll (56) arrived at a similar conclusion on the basis of a literature review and field studies in Kent, England.

In Canada, numerous cases of groundwater pollution have been reported. A comprehensive coverage of these cases has been presented by Cherry (57). Shallow groundwaters that have been contaminated by leachates from landfills include those that occur below three large landfills in the outskirts of the city of North Bay and near Alliston and Kitchenor-Waterloo in Ontario. Severe groundwater contamination from chlorophenols has been reported from Pentritton, British Columbia (57). Mine tailings are another major source of groundwater contamination in the mining districts of Canada. Extensive nitrate contamination of shallow aquifers have been observed in the Canadian prairies. This has been attributed to the use of agricultural fertilizers. Similar widespread occurrence of nitrate has been reported in a large regional carbonate-rock aquifer in England and the United States.

Leakages in nuclear power plants constitute another source of groundwater contamination. This is because the radiation would eventually be returned to the groundwater environment. Recent nuclear leakages include the Chernobyl incident in the Soviet Union. The impact of these leakages on the groundwater environment has, however, not been fully investigated. No doubt, a large number of cases of groundwater contamination have been reported. However, disposal sites that are known contamination sources probably account for only a small fraction of the total number of sites where groundwater contamination now occurs (57). It should, in addition, be expected that more severe cases

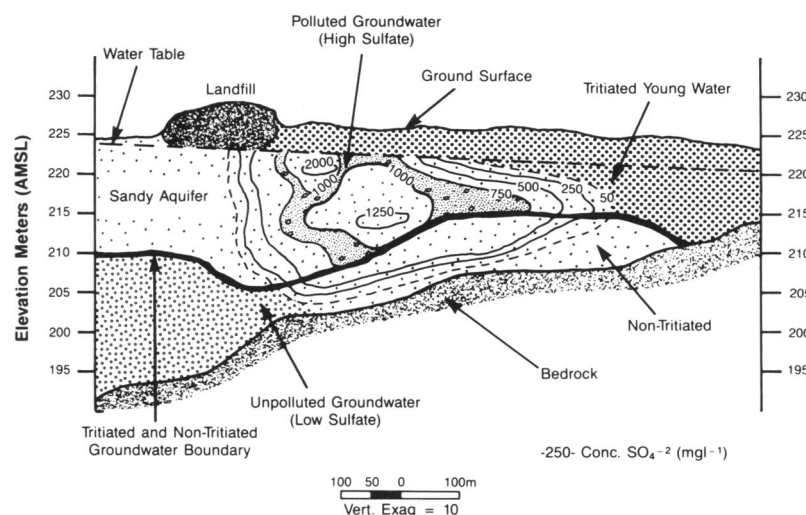


FIGURE 16. Sulfate pollution of ground with tritiated tritium boundary (41).

of pollution could arise in the future as technology brings new and more hazardous chemical compounds into production and use. At the moment, great amounts of financial and material resources have been spent on the control of pollution. Health and environmental hazards posed by pollutants and contaminants are immense as many pollution-related diseases continue to emerge. Great losses in human and animal life and property have continued. As the developed countries are engrossed in these problems, it is unfortunate that the developing countries are becoming equally affected because no articulated control programs exist to any extent.

Developing Countries

Information on environmental pollution situations of developed countries such as the United States, Canada, and parts of Europe abound in the hydrogeologic literature (20,58–65). Acid rain has obliterated many ancient forests, acidified both surface water and shallow groundwaters, and defaced many buildings and monuments. Industrial wastes dumped as solids or discharged as liquids into surface waters have destroyed the fauna and flora of these waters. Many landfills and sewage lagoons dotted all over these industrialized nations have damaged the hydrogeologic environments. Many medium-level and high-level wastes from nuclear industries are stockpiled, waiting for safe disposal sites yet to be located in any part of the world. These pollutant/contaminant materials and their attendant problems have devoured huge funds for research and control activities. Despite the available manpower and expertise and the adequate financial resources in these countries, minimal successes in combating pollution have been achieved, so pollution threats so far seem to have defied man's efforts.

The fate of developed countries magnifies the helplessness of some developing countries that have now exposed parts of their hydrogeologic environments to pollution. Many of these countries in their race to become industrialized have accumulated waste products that now pollute the environment. Many of these countries have copied the developed countries in their science and technology, packaged and acquired the resulting technological outputs, and transplanted them into their countries without the necessary checks and balances such as an appropriate adaptation to the needs of their environments. These countries produce huge volumes of pollutants and contaminants from industries and urban centers and dispose of them into surface waters or dump them at the outskirts of their cities. They do not have enough pollution management experts and the necessary finances to control the spread of pollutants. Outbreaks of diseases that are pollution based occur from time to time. It is strongly believed that unless these developing countries do something to stop the present pollution trends that are fast growing, many of their environments shall be worse off than those now prevalent in parts of the developed world. Already some countries are closely approaching this stage.

The specter of widescale pollution of environments of developing countries is becoming more threatening for many other reasons. More and more urban, suburban, and rural communities are being polluted or exposed to pollution. Few of these countries have plans or management programs to combat pollution. Pollution problems are thus tolerated and given no priority. There is little or no public or government awareness because the dangers seem to be ignored or overlooked. There are no Environmental Protection Laws and where available, they are rarely enforced. When these poor countries soon reach the level of pollutant/contaminant generation as the rich industrialized countries, they shall be much worse off. Already various health hazards and polluted waters with waterborne diseases and epidemics ravage these countries from time to time. Even though it is known that many of these pollutants are produced through industrialization and urbanization activities, governments, groups, and individuals have not been doing anything to control their emission or production. Even in rural environments where agricultural, mining, and urbanizing programs continue to generate pollutants and contaminants, no one seems to show much concern.

Some developed countries, as a result of their stiff Environmental Protection Laws, indirectly encourage the export of waste products. This practice is either carried out directly because these materials cannot be disposed of economically or safely in their home countries or indirectly through establishment of industries in developing countries. These industries produce hazardous wastes that are carelessly dumped or discharged. Such exported industries lack adequate safety devices and efficient monitoring systems. Finally, in the drinking water supply program, emphasis is placed only on water quantity and little or none on quality. Because of this emphasis water potability is questionable most of the time. Typical pollution case examples from some developing countries shall be given below to provide more credence to these unfortunate observations.

Environmental/Health Hazards and Implications

Various environmental problems can arise as a result of groundwater pollution. A major consequence of groundwater pollution includes the potential contamination of surface waters. This can happen if the rivers, streams, or lakes in the area are recharged by a polluted aquifer. The converse becomes the case if contaminated surface waters recharge an aquifer. These cases are illustrated in Figures 17a and 17b, respectively. Water pollution can result in a reduction in economic and agricultural activities. For example, when surface waters are contaminated, they can result in higher fish mortality. In third world countries, in particular, where fishing on a subsistence level provides a means of livelihood, a significant drop in fish productivity due to pollution can have unpleasant consequences on the eco-

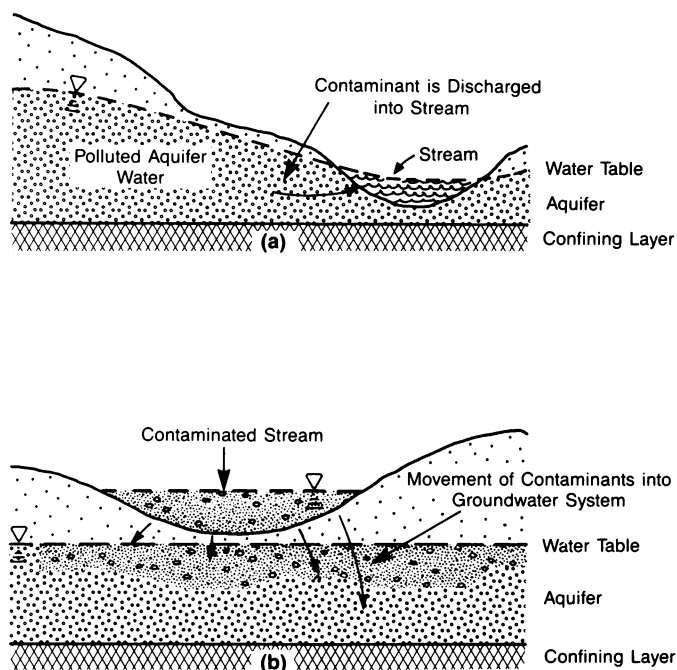


FIGURE 17. A schematic diagram showing the potential for contamination of (a) surface waters when an aquifer is polluted and (b) contamination of groundwaters when surface waters are polluted.

nomic life of the community. Polluted irrigation water poses health risks. It can also result in reduced crop productivity. Thus, water pollution can have serious negative effects on the agricultural sector too.

Other environmental hazards arising from water pollution include the presence of odor and color in the affected water. Pollution of surface waters (lakes, dams, rivers) may affect groundwater adversely. Water supplies are contaminated resulting in health risks and increased load on water treatment plants; increased costs on water treatment plants; fish kills or decline in productivity, quality and quantity; polluted irrigation water, posing health risks or inhibiting crop productivity; degradation of recreational and aesthetic characteristics of waters; etc. (1). Sometimes poisonous ions, dissolved gases, trace elements, heavy metals, and radioactive materials in water endanger the biospheric parts of the environments. Hence waterborne diseases are of epidemic occurrence in many developing countries where they form debilitating scourges to humans. Also major physiological ailments such as cancer, that may sometimes be caused by water or food have become rampant in both developed and developing countries. Many surface water and groundwater bodies are dead and remain anoxic as a result of heavy inputs of pollutants and contaminants. Many pollutants from one source can move for long distances through groundwater flow systems to polluted faraway areas, precipitating large-scale environmental destruction. Some high-level wastes have pollutants and contaminants

with long half-lives. Because of this property, they remain hazardous for long times within the hydrogeologic environment and are very difficult to remove.

In the hydrogeomicrobiologic literature, cases of microbial pollution and hazards abound that are a threat to both surface water and groundwater systems. Under certain circumstances, the pathogenic microorganisms listed in Table 3 escape the purification processes accompanying percolation of polluted surface waters into groundwaters where they constitute a dangerous health hazard. Salmonellosis, bacillary dysentery, schistosomiasis, helminthiasis, and viral infections are known to have been transmitted through drinking groundwaters polluted by surface waters and sewage in this way (66). Public interest in nitrogen oxides arises from the toxic effects of nitrite when nitrite ions enter the blood stream and react with hemoglobin, leading to an impairment of oxygen transport, particularly in infants. The disease is almost always attributable to high levels of nitrates in drinking water supplies including polluted groundwaters (23,31,35). Under certain conditions nitrate may be reduced to ammonia by some of the nitrate reducers. The ammonia can react with chlorine to produce chloramines, which can lead to undesirable tastes and odors. The presence of sulfides produced by sulfates reducers in groundwaters also impart unacceptable tastes and odors. Iron bacteria have caused problems in water supplies since the dawn of civilization, and there are many references in history to "red" water, undrinkable water covered with slime, and plugged wells (67).

In wells and boreholes, the major problems are *a*) growths that plug the screens; *b*) coatings on piping systems, impellers and motors, that reduce flow rates; *c*) reduced potability of water; and *d*) total plugging of the well. The iron and manganese bacteria that cause these problems are thought to be introduced into the wells and boreholes from their soil habitat during initial boring operations or by seepage into the aquifer feeding the well (68).

Groundwaters drawn from wells and boreholes constitute a major source of water supply in many African countries including Nigeria. In these circumstances, the water is usually untreated. The inadequate practices of waste disposal in these countries lend themselves as being a large source of pollution for groundwaters.

In Nigeria, feces are disposed of by one or more of the following ways, depending on the locality: disposal on ordinary dry ground, bucket latrines, the pit-latrines or pit-privy, and septic tank latrine (aqua privy). Domestic and industrial wastes are disposed of either by composting, sewage, or open drainage systems (66). The content of these waste products are usually organic and inorganic matter as well as microorganisms, some of which are pathogenic. Some of the wastes in refuse tips are washed into surface waters leading to eutrophication. In most circumstances in Nigeria, parts of Lagos, Ibadan, Benin, Enugu, Onitsha, Kaduna, Kano, Jos, Abakaliki, etc., adequate hydrological data are not sought on soil strata and the direction and rate of flow

of groundwaters before wells are sunk (37). The result is that sometimes wells are sunk less than 5 m away from obvious sources of pollution like pit latrines (69,70). Worse still, the wells are usually not lined at all, with the result that the groundwaters easily get contaminated by seepage from pollute surface waters.

Cases of guinea worm infestation in parts of Ilorin and Abakaliki have continually been linked to the drinking of groundwaters contaminated by heavily polluted surface waters. The outbreak of cholera in Ohaozara area of Nigeria in 1981–1984 was also linked to poorly sited wells in the area (25). It is obvious that, if systematically investigated, most outbreaks of waterborne diseases could be linked to pollution of groundwaters from surface waters, septic tanks, pit latrines, and compost heaps. It is in recognition of this danger that the Federal and State governments of Nigeria as well as many international organizations like the WHO and UNICEF are currently tackling health problems in Nigeria by the provision of properly sited boreholes in all the rural communities.

In 1977 the Food and Drug Administration Unit of the Federal Ministry of Health in Kaduna Nigeria (25) reported a widespread occurrence of iron bacteria in up to 60% of the boreholes in the Funtua, Bida, Malumfashi, Dutsi-ma, Daura, Katsina, and Kano areas (23). Except in the Kano areas, the genera of iron bacteria encountered were *Siderocapsa* and *Siderococcus*. These microbial pollutants have caused many groundwater supplies problems, resulting in loss of well yields, water contamination, and increased costs of water supplies. These problems are worsened by the absence of continuous monitoring programs.

In the Kano area, the filamentous iron bacteria *Lepidothrix* and *Crenothrix* were found abundantly in nearly all the boreholes in the Bompai area, on the outskirts of Kano municipality. The pollution was traced to the myriad of refuse tips made up of the waste products from the sugar, sweets, and biscuit factories in Kano. The global distribution of iron bacterial problems in groundwater was reported by Cullimore and McCann (67). Among the developing countries included in the draft are El Salvador, Guyana, India, Malaya, Nigeria, Singapore, and Sri Lanka. *Crenothrix* was found to be plugging water supply systems in Sri Lanka; *Clonothrix* reduced flow rates and potability of water in the Calcutta area of India. In all others, the offensive iron bacteria were not specified, but the damage they caused was observed.

The industrialized world has accumulated great amounts of pollutants and contaminants within their environments. Many of these pollutants have spread widely and in such a complex manner that their control will be a most difficult and costly venture. Many wastes are now piled up in storage tanks above and below the ground surface, while painstaking research efforts are being made to scout out possible safe geologic environments for their disposal. Unfortunately, so far, as a result of the structural, stratigraphic, sedimentological, and geotechnical properties of the pedologic and geo-

logic units, no safe disposal environments have yet been found for waste products that have long half-lives. It seems that until a safe and more reliable disposal method is found, both the developed and developing countries, have no option but to reduce the volume of wastes both societies are now generating and abandoning or storing within hydrogeologic environments.

Pollution Case Examples from Some Developing Countries

Parts of urban and rural environments of many developing countries such as India, Kenya, Nigeria, Sudan, Egypt, Iraq, and Brazil are being polluted with a wide variety of hazardous substances. Such countries are struggling to become industrialized without adequate plans to contain the spread and hazards of pollution. There are many sources of pollution in developing countries. Some of those related to mining, mineralization, agricultural, domestic, municipal, human, and animal wastes shall be discussed. Typical case examples shall also be briefly described, and these shall be generally related and at some instances specific to some developing countries that are now industrializing at a rapid rate.

Mining Pollution

Contamination of groundwater due to mining activity is a major problem in many developing countries. Previous or present mining activities result in contamination from waste dumps, mine workings, fragments, and dust from ore and rock piles and smelter operations. Sulfides (usually pyrite, galena, and sphalerite) in mine dumps are especially susceptible to oxidation and produce acid mine waters that can be leached out in varying volumes and amounts. The ore minerals are not completely recovered during the beneficiation processes. The acid mine waters that also contain trace metals make their way into groundwater flow systems.

Acid mine waters from an abandoned mine in the Charcas District, San Luis Potosi, resulted in high metal values in drainage systems and groundwaters (71). The acid mine drainage problems in Enugu coal mines of Nigeria and their effects on groundwater pollution were highlighted by Egboka and Uma (21). Many coal beds may contain up to 10% sulfur, chiefly in the form of pyrite and marcasite. As the coal deposit is worked, air and water gain access to the seams that contain sulfur minerals, oxidizing the sulfide minerals. This results in the formation of enormous amounts of sulfuric acid. Groundwater recharged by water from the mine needs considerable treatment with lime before it can be used to supply domestic homes and industries. In the acid mine drainage problems in the Enugu coal mines of Nigeria, about 18.1 million liters of acid water with high iron content is pumped out daily into nearby rivers. Some of this acid water eventually enters groundwater flow systems. The acid waters also attack and corrode mining equipment causing great financial losses. Some

mine waters are colored brown by tannins from bark of trees. They have an objectionable taste and they render the water unfit for drinking. Sometimes the waters actually are sterile enough for use even though they are colored and may have a bad taste. Phenols are abundant in waters in coal swamps. Phenols are poisonous to many bacteria and are capable of making mine waters sterile if they are present in large quantities.

In most developing countries there is no legislation guiding the safe disposal of mine wastes and mine dumps or their proper management. Most of the mining companies involved are mostly foreign firms. The companies do not show much interest in tackling environmental pollution problems associated with the mining wastes they produce annually. Little or no money is spent on wastes research and management in many parts of Nigeria and other countries. The uneducated rural people often use polluted waters discharged from mines. Many people from Abakaliki Mining district of Anambra State, Nigeria, suffer from lead poisoning resulting from the contamination of their water sources by lead. The area is also ravaged by guinea worm and other waterborne diseases.

Domestic, Municipal, Human, and Animal Waste Contamination

Domestic wastes contribute a large number of elements to groundwater systems, all with unpleasant ramifications. The most common contaminants from household products include phosphates and boron in laundry detergents, copper and other elements as organometallic compounds in garbage; metals in urine and excreta; copper, lead, zinc, and asbestos from pipes; nickel from stainless-steel pipes and well casings. Municipalities that treat sewage and garbage reduce metal concentration in drinking waters, but the recent tendency to dispose of the treated material on land eventually yields metals to the drainage basin. Such metals may eventually reach the surface water and groundwater flow systems and pollute them. Similarly, metals are introduced into the hydrogeologic environment from the resultant ashes when garbage or solid wastes are composted as is commonly done in developing countries.

The tremendous increase in the use of septic tanks for home sewage disposal has contributed a great deal of dissolved polluting materials to groundwater (Fig. 8).

The septic tank waters seep into the soil and where water supply aquifers are shallow, will contaminate groundwater with phosphate and boron from detergents and a variety of other substances such as nitrates that are undesirable or harmful to health. In many rural communities in developing countries shallow pit latrines are used for disposal of human excreta. Other undesirable materials like expired drugs and unwanted chemicals are also dumped into pit latrines or shallow waterways. Human excreta collected in bucket toilets are also emptied into the pit latrines. Water infiltration into the ground through the pit latrines introduces a number of

undesirable compounds into groundwaters (18,69,70,72).

In many cities all kinds of waste materials are strewn about on the outskirts of towns or are thrown into streams, lakes, and rivers as most of those cities originated and developed close to major rivers. Aerosol cans, drug containers, hospitals, and research laboratories, washings or wastewaters that may contain heavy metals such as mercury, lead, zinc, etc., may eventually decay or spread and become transported into groundwater flow domains. Underground and surface storage tanks, septic systems/fields, etc., washings from motor mechanic sheds and garages produce contaminating leachates (Fig. 7). These types of pollutants have threatened hydrogeologic systems in parts of Nigeria (69,70,72). In some urban areas of developing countries such as India in temperate climates, large quantities of road salt (NaCl and CaCl) are used for deicing the road in winter. Leachates from these activities will eventually contaminate aquifers. Egboka (15) briefly described the traditional habit of using the bush for toilet purposes in many rural areas and suburban centers. It is believed that defecation of this type contributes to widespread and prevalent waterborne diseases in such areas. It also accelerates large-scale incidences of eutrophication in lakes. Unfortunately, it is yet to be estimated the degree and extent of environmental pollution through defecation in the rural areas.

Agricultural Contamination

The use of pesticides, herbicides, fertilizers, and other materials to increase agricultural yields has some great negative effects on groundwater quality. Pesticides and herbicides applied to fields or orchards may find their way into groundwater when rain or irrigation water leaches the dissolved constituents downward into the soil. Nitrate from its fertilizer, one of the most widely used agricultural fertilizers, is harmful in drinking waters even in relatively small quantities. The nitrate is very soluble and although some may be used by plants, much of the dissolved nitrate escapes unused into deeper parts of the soil and into groundwater. Sewage and fertilizer can increase nitrate levels in some aquifers (4). Nitrate is toxic to humans even in amounts as small as 10 to 15 ppm.

Uranium and fluorine in phosphate fertilizers and probably rubidium in potash fertilizer are soluble under most conditions and will eventually find their way into the groundwater regimes. The use of lime for the production of fertilizer may result in lead and zinc contamination, if the lime is produced from metal-containing limestones. Mississippi-type lead-zinc deposits are common in limestones. Some limestone deposit used for production of lime may contain appreciable quantities of lead-zinc minerals.

In developing countries, the people and governments place their priorities on food production in enough quantities to stem the tide of hunger and mass deprivation and little or no consideration is given to the pollution

implications. The poor farmers, most of whom practice subsistence agriculture, are highly encouraged to apply fertilizer and use insecticides/herbicides for maximum crop yields. The prices for these chemicals are very low and affordable as the governments have subsidized the costs. Thus, the chemicals may be used indiscriminately. A large amount is released to the environment to pollute surface water and shallow groundwaters. This practice is common in many developing countries.

Radioactive Contamination of Groundwater

Another source of groundwater contamination is radioactive wastes from power plants and mine dumps. One of the serious long-range problems associated with the use of nuclear power plants is the disposal of highly radioactive nuclear wastes. These highly toxic wastes are by-products of nuclear power plants and the manufacture of nuclear weapons. These radioactive wastes are temporarily stored as liquids in tanks. Despite the fact that the waste must be isolated from humans and other organisms for many centuries before it is safe, it has not been possible to store the wastes for even a few decades without mishap. Several thousand gallons of waste do seep into groundwater from storage tanks before anyone realizes there is a leak. Radioactive materials in water even in very small amounts are harmful to all forms of life. Some developing countries are believed to have nuclear power.

The problem of disposal of radioactive wastes is especially common in industrialized countries, but the disposal of radioactive wastes in uranium mines is a problem that occurs more in developing countries. Some developing countries are producers of uranium and other raw materials needed for nuclear power plants. In most of these countries, there are no regulations governing the disposal of mine wastes. They are dumped around and abandoned by the operators in the mine environment.

Uranium is usually present in the tetravalent state (U^{4+}). In this valence state, uranium is not soluble, and is immobile. When exposed during mining and dumped in mine waste, uranium is oxidized to the hexavalent (U^{6+}) state occurring as uranyl ion (UO_2^{2+}). Uranium then moves from an oxygen-rich surface environment, in which uranium is in the hexavalent state or complexed with carbonate into the subsurface groundwater environment. The problem of contamination of groundwater in uranium mining areas by uranium and its daughter products in active and abandoned mines is as serious as those associated with nuclear wastes. In nuclear power plants, adequate precautionary measures are always taken in handling the radioactive wastes. In uranium mining areas no such precautions are taken and the danger of contamination of groundwater by radioactive materials leached from mine dumps is great. The problem is most serious in those developing countries where the inhabitants of mining areas are not aware of the problems. When it is realized that some

developing countries have nuclear capabilities and hence are generating high-level radioactive wastes, it becomes a matter of great concern to conjecture how these wastes are being isolated from the biospheric environment. So far, it is a top secret matter and those few developing countries that have nuclear capability hardly provide any information to the public.

Pollution/Contamination from Natural Sources

Pollution and contamination may come from natural sources such as during physicochemical weathering and mass wasting, soil and gully erosion, flooding, snowfall, wind activities, and seawater intrusion through wave action, volcanic or gas eruptions, geochemical evolution through groundwater infiltration, and percolation. A large quantity of pollutants and contaminants are released from these sources but it is very difficult to quantify and control release by natural processes. During weathering, geologic units are corroded, weathered, disintegrated, and disaggregated, thereby releasing dissolved geochemical constituents into the hydrogeologic systems. During sediment transport and deposition, geochemical reactions (38,49) may result in the release of more ions and dissolved gases that may become concentrated enough to be hazardous. In addition, soil and gully erosion (16,17) may remove volumes of sediments with potential pollutants and contaminants that may threaten the environment. In some situations deep gullying that intersects the watertable and shaley terrains may result in hydrogeomicrobiological reactions that may release deleterious pollutants into groundwater (17).

Snowmelt and rainfall and anthropogenic activities such as farming, excavation, and mining accelerate the transport of sediments and enhance their pollution potentials. Thus, in parts of the humid tropics, floodwaters are densely brownish in color, reflecting high sediment loads. Wind activities in areas at the fringes of deserts also transport sediments that pollute the environment. Nigeria, Chad, Sudan, Niger, and other countries that are close to the Sahara Desert suffer from these problems. These types of pollutants are very serious, particularly in developing countries because there does not exist any plan to combat them. Some of these countries may not even recognize their existence or just ignore them. Meanwhile the pollutants continue to ravage their environments.

Case Examples: Review of Pollution/Contamination in Some Developing Countries

India has emerged as an industrial nation and a major producer of manufactured and agricultural products within the last 20 years. Because the population is large and industrial activities are intense, large volumes of gaseous, liquid, and solid wastes are continuously re-

leased into the environment. Surface waters and shallow and deep groundwaters have been polluted in urban and rural areas (73–75). Neighboring countries of Pakistan and Bangladesh are equally polluted or threatened. The excessive withdrawal of groundwater in the Saurashtra area of India has resulted in sea-water intrusion. Parts of the groundwater in Gujarat State are mineralized and polluted by high temperature waters. The groundwaters from the Khetri copper mines in Rajasthan, Mahakali coal field area of Maharashtra, and the Panandhro lignite field pose geotechnical and pollution problems. Currently, as a result of tourist activities, many ancient forest lands, hills, valleys, and even mountains are being strewn with garbage thrown away by tourists thereby polluting the environments.

Kenya is a typical industrializing East African country producing varying degrees of pollution. Other neighboring countries of Uganda, Zimbabwe, Tanzania, Malawi, and Botswana are not spared. In a water resources quality survey by Nair et al. (76) from 1286 boreholes from parts of Kenya, the majority of the samples (61.4%) have fluoride values above 1.0 ppm while 19.5% had above 5.0 ppm and sometimes in even greater amounts (76). Table 7 lists the summary of maximum fluoride levels taken from each province and in different locations in Kenya. The high fluoride areas coincided with volcanic rock areas. The high fluoride water caused extensive public health hazards such as deformity in children. In Malawi, localized pollution of groundwater affects the quality adversely. Waters of up to 4000 to 7000 $\mu\text{mhos/cm}$ of electrical conductivity occur. High sulfate iron and magnesium concentrations are common (77). Foster et al. (78) reported serious nitrate and fecal pollution of shallow groundwaters in parts of Botswana through pit latrines.

Many hydrogeologic environments in Nigeria are polluted (10,15,18,19,22,69,70). Saline lakes and hot springs occur (79,80). Coastal towns such as Lagos and Port Harcourt suffer from saltwater intrusions from the Atlantic ocean. Inland waters such as rivers (Kaduna, Niger, Anambra) and lakes (Chad, Agulu) have received pollutants in varying degrees. Industrial wastes are indiscriminately disposed of on land or into surface waters. Sewage is similarly disposed of. Mineralized waters attack and destroy borehole networks in the Maiduguri areas of northern Nigeria. The rural com-

munities are equally not spared as present attempts to develop rural areas have introduced many pollutants and contaminants into the environment. Soil and gully erosion and flooding have become rampant and pollute surface waters and groundwater. Outbreaks of water-borne disease such as cholera, yellow fever, dysentery, diarrhea, and Guineaworm occur periodically, resulting in fatalities. Mining companies in Jos, Abakaliki, Enugu, Nkalagu, and the Port Harcourt areas pollute the environments without restraint. Flaring of gases and oil spills have contaminated surface waters and groundwaters (10). There is yet no effective legislation to check these problems.

In a geochemical study of the Otamiri and Aba river watershed in southeastern Nigeria by Nwankwor and Okpala (81), nitrate concentrations in the order of 100 mg/L were found in the groundwater and surface water systems of the Otamiri watershed. Nitrate loading of the waters in the Otamiri watershed were attributed to intensive use of fertilizer by various government-sponsored agricultural establishments in the basin. Results from the Aba River, which drains the largely industrial city of Aba, showed abnormally high concentrations of Co^{2+} and gave values for pH that varied between 4.0 and 6.5 (81).

Egypt and the neighboring countries of Sudan and Libya have polluted surface waters and groundwaters. Primary sources of pollution are industrial/sewage wastes, agricultural/irrigation activities, and salinization processes. Volumes of waste products are drained into the River Nile and eventually into the sea through a complex network of canals. Some of the irrigation waters react with soil water/groundwater and with soil materials dissolving the soluble salts, salinizing the soil, and increasing the salt concentration in irrigation canals and groundwaters (82).

Alexandria, with a population of about 3 million people, is the main industrial center and is burdened with pollutants and contaminants from many sources. Parts of Meryut Lake have been destroyed by sewage, thereby contaminating fish. According to Preul (82), groundwater levels in lower Egypt rose considerably with the building of the Aswan dam in 1965. The regional rise in water levels of shallow aquifers compounded the problems of pollution spread through subsurface disposal of wastewaters and irrigation water. Villages "are experiencing considerable difficulties with wastewater disposal due to subsurface saturation, high groundwater, emerging surface pools of septic waters, gross groundwater pollution, deterioration of buildings and structures due to moisture absorption, and other related problems. A further complication in certain areas is the existence of a large irrigation canal which usually carries a level of flow above the general elevation of the village and therefore creates a hydraulic gradient of seepage through the dykes towards the village" (82).

Even though the government of Egypt has environmental protection laws, their enforcement, particularly in the rural areas, needs to be encouraged. These rural

Table 7. Maximum fluoride concentrations in Kenyan water samples taken from each province (76).

Province	District	Fluoride concentration, ppm
Nairobi		30.2
Central	Nurang'a	22.0
Coast	Taita Taveta	15.0
Eastern	Machakos	19.3
Northeastern	Wajir	38.2
Nyanza	Kisumu	10.4
Rift Valley	Nakuru	57.0
Western	Bungoma	7.1
Nationally		57.0

communities continue to be exposed to increasing soil, surface water and groundwater pollution.

Al-Jabari and Al-Ansari (83) described the dissolution of geological outcrops and soils in Iraq. These are rich with calcium carbonate and gypsiferous deposits. Water inputs from flood plains and valleys with organic matter contents reaching up to 20%, high suspended sediments, inputs from springs (Table 8), and human activities pollute the environment. Their pollution potentials are enhanced by erosion. Tremendous amounts of dust generate fallouts from sediments in central Iraq at the rate of 2.1 cm/yr (83-85). The sediments contain pollutants and contaminants in the form of carbonates (calcite, dolomite grains) quartz, feldspars, gypsum, chert, muscovite, heavy minerals (pyroxenes, zircon, biotite, hornblende, epidote, rutile, garnet, chlorite, staurolite and Kyanite), and pyrites (83-85). The heavy minerals assemblage in the outfalls have been correlated with the heavy mineral content of the Tigris and Euphrates Rivers flood plains and older dune deposits (Table 8). Salman et al. (84), in their investigation of bacterial density in Tigris River within Bagdad, measured a high density of coliform bacteria and *Escherichia coli*, suggestive of fecal pollution from sewage disposal. The bacterial density correlated well with high suspended sediment loads, which are believed to transport the bacteria in water. The high sediment concentration is accelerated by anthropogenic activities such as dredging, swimming, and solid/liquid disposal on land and water.

Pollution of surface water and groundwater in the developing countries of South America have also been reported. Argentina, Brazil, Chile, Cuba, Nicaragua, etc., have been equally exposed. Brinkman (86) discussed the hydrogeochemistry of groundwater resources in the central Amazonian area of Brazil. Ducloux (87) also treated the central zone of La Pampa Province of Argentina. Other countries in Africa such as Ghana, Zaire, Sudan, Mauritania, Ivory Coast, etc., have been unduly exposed to the destructive hazards of environmental pollution (88,89).

Summary and Suggestions

According to Fano et al. (1), "it may be expected that over the next decade the management of water quality

problems will be one of the outstanding issues relating to the protection and conservation of the national stock of water in each country . . . The rapid aggregation of population in major urban centers, the polarization of industries, and the heavy dependence of chemical products, particularly in the agricultural sector, are leading to a serious deterioration of water quality in developing countries." Already parts of the environments of many industrialized nations are highly polluted. The problems are being tackled with available manpower, expertise, and financial resources in these countries. Encouraging successes are yet to be achieved, as the pollutants continue to diffuse and disperse into the hydrogeologic environment, and several tons of high-level wastes are piling up in storage tanks while desperate efforts are being made to locate geologic formations for safe waste disposal.

Unfortunately, in an obvious attempt by many developing countries to industrialize and compete with the developed nations, waste products are being generated in large quantities. These countries have neither the manpower, expertise, nor the financial resources to control or safely dispose of these deleterious wastes. As a result, their environments are becoming heavily polluted at an alarming rate. The leadership of these countries seem to lack the will or the serious understanding to recognize and mount a control program. Because of this, pollution continues to spread unabated with its attendant hazards and problems. In the next 10 years, unless something is done quickly, pollution levels in many developing countries' hydrogeologic environments would have reached such destructive levels that they may become uncontrollable. Destruction of plants, animals, and humans through pollution-caused epidemics/diseases would have become commonplace as requisite funds and materials for their control may not be available.

Developing countries must now learn from the mistakes of the developed nations *vis-a-vis* pollutants and contaminants, to save their environments from pollution damages for future generations. Some of the following pollution-control programs being pursued or implemented in many industrialized countries should be of worldwide application. The present consciousness about the hazards of pollutants and contaminants in developed nations must be highly encouraged. Every effort must be made to reduce pollutant/contaminant loads into the environment through improvements in manufacturing techniques that could recycle waste products. More efficient techniques for the destruction of high-level pollutants and contaminants before they can reach the hydrospheric zones should be found through more research. Through more intense investigations, safe pedologic, and geologic formations for disposal of wastes can be located. The present careless dumping of wastes into surface waters or the poorly engineered subsurface burial of wastes must be stopped. These practices have damaged many hydrogeologic environments as these materials spread locally and regionally. The effects of geologic and pedologic structures and characteristics on

Table 8. Water discharge and solute concentration of springs on River Euphrates (83).

Spring no.	Average discharge, L/sec	Average TDS, ppm
1	—	3110
2	24	3272
3	—	3378
4	3700	3927
5	4	3002
6	100	3880
7	26	27910
8	360	3662
9	—	—
10	100	3445
11	—	3662
12	4	2690
13	29	3080

the dispersion of pollution must be recognized in order to be able to apply the correct engineered control methods.

At the moment, there is a loose/poorly coordinated, nonintegrated approach in the control of pollutants and contaminants by various professionals involved in pollution research and control. Hydrogeologists, chemical engineers, civil engineers, soil scientists, etc., do not seem to work together. The multidisciplinary and multiobjective techniques are not appreciated by pollution control planners and managers, particularly in developing countries. This unfortunate behavioral tendency may result from poor training or professional pride and hence must be discarded. Professionals working in pollution control must appreciate the contributions of others to maximize their successes. This could be achieved by proper training through improved curricula in higher education that exposes all trainees to the origin, life, spread, and hazards of pollution in the environment and the need to develop appropriate coordinated integrated control methods. Seminars, workshops, symposia, and short courses should be organized to educate all professionals, planners, and managers of pollution problems. Countries and international aid agencies should give these the desired priority.

The developed countries should assist developing ones in controlling pollution. Manpower, expertise, and some financial resources should be made available to these poor countries to aid them in planning and management of waste disposal programs. Industrial concerns in developing countries must now discard their polluting tendencies in many developing countries and cooperate in pollution control. Most of their industrial activities exacerbate incidences of pollution. Environmental Pollution Control laws must be enacted by developing countries to protect their environments. Such laws, when made, must also be effectively enforced. Egypt has established such laws and has been fairly successful in enforcing them and achieving beneficial results (1). Strong emphasis should be placed on public health and education programs and enlightenment. Even though pollution is becoming widespread in developing countries, there is still a paucity of data and records, poor documentation and information exchanges. Research centers and institutes devoted primarily to teaching and research on pollutants and contaminants are still not given any priority. Such institutions should be established urgently to work on the various aspects of pollution with particular emphasis on its genesis, spread, hazards, and control in relation to the geologic, hydrologic and hydrogeopollution cycles (Figs. 1, 4, and 5) (91).

Coordinated sampling and monitoring programs are required by zones, nations, and regions to check widespread/regional pollution. Hence, local, international, and regional pollution events should be traced and monitored on a continuous basis and warning signals against hazards issued to areas affected. Information exchanges should be encouraged between nations, among experts/professionals, governments, and aid-giving agencies.

Research programs in both developed and developing countries must give attention to sources and types of pollution, modes of occurrence and spread, dynamics of transport and dispersion, pollutants-life-expectancy, and means of disposal of wastes. Development of effective control technology should be continuously and adequately funded.

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